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FOR SOLAR CELL ENCAPSULANTS Annual Report
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ANNUAL REPORT

INVESTIGATION OF TEST METHODS,
MATERIAL PROPERTIES, AND PROCESSES
FOR SOLAR CELL ENCAPSULANTS

JPL Contract 954527

For

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, California 91103

ENCAPSULATION TASK OF THE LOW-COST
SILICON SOLAR ARRAY PROJECT

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I. SUMMARY

Springborn Laboratories is engaged in a study of evaluating potentially useful encapsulating materials for Task 3 of the Low-Cost Silicon Solar Array project (LSA) funded by DOE. The goal of this program is to identify, evaluate, and recommend encapsulant materials and processes for the production of cost-effective, long-life solar cell modules.

During the past year, the technical activities emphasized the reformulation of a commercial grade of ethylene/vinyl acetate copolymer for use as a pottant in solar cell module manufacture. Potentially successful formulations were prepared by compounding the raw polymer with antioxidants, ultraviolet absorbers and cross-linking agents to yield stabilized and curable compositions. The resulting elastomer offers low cost (approximately \$0.80/lb.), low temperature processability, high transparency (91% transmission), and low modulus. Cured specimens of the final formulation have endured 4000 hours of RS/4 fluorescent sunlamp radiation without change. This indicates excellent stability, however, correlations with outdoor exposure are being evaluated under other phases of the LSA program.

The compounded resin was prepared in two grades; one clear to provide a covering over the cell, and one pigmented white to serve as a reflective background behind the cell. These compounded resins were then converted to a more useful form with an extruder to give pottant in sheets that could be more easily used in lamination.

After experimenting with a variety of techniques, a vacuum-bag process was developed and found to be an excellent encapsulation method. Miniature single-celled and multi-celled solar modules of both substrate and superstrate designs were prepared by this technique. The resulting modules were of good appearance, were bubble-free, and successfully passed the JPL thermal cycle test. This method offers a reasonably fast fabrication time (40-50 minutes) and has the potential for automated production.

Adhesive strengths and primers for the bonding of ethylene/vinyl acetate to superstrate and substrate materials was assessed with encouraging results. The incorporation of silane compounds either directly into the polymer as a blend or

as a surface coating gave high bond strengths (20 to 30 lbs/in) to glass. The bonds endured 24 hours of boiling water with no delamination. Adhesion to hardboard was also excellent, however, the bonds were severely weakened by water immersion, the failure occurring within the surface of the hardboard. Some method for providing isolation from liquid water will be required to make hardboard products viable substrates.

The weathering effects on ten other polymers exposed to twelve months of weathering in Arizona, Florida, and under EMMAQUA were evaluated by determination of tensile strengths, elongations, optical transmission, etc. As may be expected, the best overall retention of mechanical properties is found for the fluorocarbon polymers, especially FEP. Two Plexiglas acrylic compounds performed almost as well and also maintained high optical transmission values. PVC, polycarbonate, and cellulose acetate butyrate specimens all degraded badly, losing almost all mechanical properties.

Two-celled minimodules constructed with these polymers survived the same exposure conditions with results varying from unaffected to complete deterioration. The electrical outputs (short-circuit currents) remained high (80-100 percent) however, regardless of encapsulant condition.

Hard coatings containing ultraviolet absorbers were investigated for the purpose of providing a soil resistant surface and additional weathering stability to the soft EVA pottant. Solution coatings of acrylics were studied and all found to be too brittle to be durable and, in addition, were difficult to apply to the module surface. Two commercial films, Tedlar 100BG30UT and Korad 201-R have the potential to provide the required protection. The Korad (acrylic) film will probably prove to be more weatherable, but has the deficiency of losing its UV absorber after several years of outdoor exposure. Experiments are being conducted to achieve permanence of the UV absorber within the film. Korad 201-R costs approximately \$0.05 per ft² in three mil thickness.

Corrosion studies using a standard salt spray test were used to determine the degree of protection offered to a variety of metals by encapsulation in EVA pottant. Excellent protection was found for copper, aluminum, solder and galvanized steel. The specimens were unaffected after 1800 hours of exposure. Mild steel (unprimed) did not perform quite as well, with rust forming in about 450 hours.

A survey of scrim materials was also conducted. These open hole weaves are intended for use as spacers between the cell and substrate to provide a mechanical barrier, improve insulation resistance and prevent migration of the pigmented pottant over the cell surface. Difficulties with deformation of the weave were encountered with the use of woven materials. Non-woven glass cloth products solved these problems, and a material tradenamed "Craneglass 230" appeared to be the most suitable. This 5 mil thick cloth is available at a cost of \$0.0078 per ft² and is effective in replacing one layer of pottant. The encapsulation cost saving is estimated at \$0.034 per ft² of module surface.

A mechanical engineering analysis of composite structural materials for use as substrates was performed. This approach offers an alternative to the single sheet materials examined in previous work and demonstrates the feasibility of constructing substrate based solar modules within the LSA cost goal from conventional building materials.

Although the use of EVA as the pottant appears quite encouraging, other materials are also under investigation, including an aliphatic urethane, ethylene/propylene-diene rubber and a polyvinyl chloride plastisol. These compounds may provide manufacturers with alternative approaches for cell encapsulation.

II. INTRODUCTION

The goal of this program is to identify and evaluate encapsulation materials and processes for the protection of silicon solar cells for service in a terrestrial environment.

Encapsulation systems are being investigated consistent with the DOE objectives of achieving a photovoltaic flat-plate module or concentrator array at a manufactured cost of \$0.70 per peak watt ($\$/\text{ft}^2$) (1980 dollars), with a projected first year production rate of 500 peak megawatts. The project is aimed at establishing the industrial capability to produce solar modules within the required cost goals by the year 1986.

To insure high reliability and long-term performance, the functional components of the solar cell module must be adequately protected from the environment by some encapsulation technique. The potentially harmful elements to module functioning include moisture, ultraviolet radiation, heat build-up, thermal excursions, dust, hail, and atmospheric pollutants. Additionally, the encapsulation system must provide mechanical support for the cells and corrosion protection for the electrical components.

Module design must be based on the use of appropriate construction materials and design parameters necessary to meet the field operating requirements, and to maximize cost/performance.

Assuming a module efficiency of ten percent, which is equivalent to a power output of 100 watts per m^2 in midday sunlight, the capital cost of the modules may be calculated as \$70.00 per m^2 . Out of this cost goal only 5.4 percent is available for encapsulation due to the high cost of the cells. The encapsulation cost allocation may then be stated as \$3.80 per m^2 (\$0.35 per ft^2) which includes all coatings, pollutants and mechanical supports for the solar cells.

Assuming the flat-plate collector to be the most efficient design, three different basic design variations have been considered:

- . Substrate Bonded: cells bonded to rigid substrate with transparent pottant and top cover.
- . Superstrate Bonded: Cells bonded to under-side of transparent superstrate with optional top cover and with back side pottant and optional back cover.
- . Laminated; rigid single transparent laminating encapsulant with optional top cover.

Photovoltaic modules are presently envisioned as being composed of six basic construction elements. These elements are (a) outer covers; (b) structural and transparent superstrate materials; (c) pottants; (d) substrates; (e) back covers; and (f) adhesives. Current investigations are concerned with identifying and utilizing materials or combinations of materials for use as each of these elements.

Extensive surveys have been conducted into many classes of materials in order to identify a compound or class of compounds optimum for use as each construction element. Properties being considered were cost, transparency, weatherability, and applicability of processing. Additional critical properties include dielectric strength, reflectivity and heat transfer characteristics.

The results of these surveys have also been useful in generating first-cut cost allocations for each construction element, which are estimated to be as follows (1980 dollars):

| Construction Elements | Cost Allocation (\$/Ft ²) |
|-----------------------|---|
| Substrate/Superstrate | 0.19 |
| Pottant | 0.08 |
| Adhesive | 0.06 |
| Outer cover | 0.01 |
| Back cover | 0.07 |

From the preceding work, it became possible to identify a small number of materials which had the highest potential as candidate low cost encapsulation materials. The following chart shows the materials of current interest and their anticipated functions:

Candidate Encapsulation Materials

| <u>Structural Element</u> <u>Superstrate Design</u> | <u>Elastomeric Pottant</u> | <u>Cover</u> | <u>Adhesives</u> |
|--|-----------------------------------|---------------------|------------------|
| Soda-Lime Glass | Ethylene/vinyl acetate | Mylar | As required |
| | Ethylene/propylene diene | Tedlar | |
| | Polyvinyl chloride plasti- sol | Aluminum foil | |
| | Poly-n-Butyl acrylate | | |
| | Silicone/Acrylate blends | | |
| | Aliphatic Polyurethanes | | |
| <u>Substrate Design</u> | | | |
| Fiberboard | | Korad 201-R | |
| Flakeboard | (same as above) | Tedlar 100 BG 30 UT | |
| Mild steel | | | |
| Glass reinforced concrete | | | |

This report presents the results of the past year's work, which has been directed predominantly at the development of ethylene/vinyl acetate copolymer as a pottant and an investigation of the systems and processes in which it may best be used. Ethylene/vinyl acetate (EVA) was selected initially over the other candidates due to its low cost, desirable physical properties, and proximity to industrial readiness. The following technical efforts will be presented:

- (1) Development of ethylene/vinyl acetate (EVA) copolymer. An encapsulation grade of EVA was selected for study as a pottant from a list of low-cost thermoplastic polymers originally identified in materials surveys. This material offers low cost, high transparency, low-temperature processability, and the potential to be upgraded to provide a long service life outdoors. Experiments were conducted to develop formulations having high melt flow, UV stability, and the ability to cure to a dimensionally stable composition.
- (2) Sheet extrusion of EVA - studies of the extrusion processing of EVA were conducted to produce the polymer in sheet form from which it could be directly used in module fabrication.
- (3) Vacuum bag process development in which EVA or any other thermoplastic resin in sheet form, may be used to encapsulate solar cells and fabricate modules in a single operation. This method has a fast cycle time and is expected to be ammenable to an automated production line.

- (4) Adhesion studies to assess bond strengths and primer efficiency of the pottant to substrate and superstrate surfaces.
Initial investigations of silane coupling agents were conducted with EVA to determine the strength and reliability of these cost-effective primers.
- (5) Evaluation of tensile specimens and two-celled experimental modules exposed to weathering conditions. This experiment provides a baseline of experience with the actual effects of weathering on various candidate cover and pottant materials. In addition to the measured changes in physical and optical properties, the effect of polymer degradation on cell performance was determined from measurements of short-circuit current.
- (6) Further investigation of outer cover formulations. In order to insure the long life of EVA, or other low cost pottants, protection from dust retention and ultraviolet light exposure is required. This is provided by the outer cover.
- (7) Corrosion studies. Specimens of metals completely and partially encapsulated in EVA were exposed to salt spray in order to determine the degree of corrosion protection afforded by the coating.
- (8) The investigation of "scrim" materials to serve as spacers between the cell and substrate. These materials help to provide mechanical and electrical insulation to the cell, prevent the flow of the white EVA layer, and lower the encapsulation cost by eliminating a layer of pottant.
- (9) Substrate analysis. Rigid substrate materials supporting the cells are probably the most expensive construction element, estimated to be at least half of the cost allocation for the encapsulation package. Past work has concentrated on the cost analysis of single homogeneous materials. This report presents an engineering and cost analysis of composite and structurally designed substrates aimed at a more efficient utilization of construction materials.
- (10) Investigation of alternate pottants. Ethylene/propylene diene rubber (EPDM) was used to prepare a baseline formulation from which extrusion and module fabrication studies were conducted. Baseline formulations of aliphatic urethane polymers were also used to construct test modules which are currently under thermal cycle testing.

III. ETHYLENE/VINYL ACETATE ENCAPSULATION MATERIALS

a. Base Polymer and Formulation

Pottants are materials which provide a number of functions, but primarily serve as a buffer between the cell and the surrounding environment. The pottant must provide a mechanical or impact barrier around the cell to prevent breakage, must provide a barrier to water which would degrade the electrical output, must serve as a barrier to conditions that cause corrosion of the cell metallization and interconnect structure, and must serve as an optical coupling medium to provide maximum light transmission to the cell surface and optimum power output. Pottants must obviously have very high transparency, with the exception of superstrate bonded designs in which cells are electrostatically bonded to the transparent superstrate and have no pottant over the front surface.

After an extensive investigation of transparent elastomers, ethylene/vinyl acetate (EVA) was selected from a class of low-cost polymers as being a likely candidate potting compound for use in the fabrication of solar cell arrays. Its selection was based on cost (approximately \$0.50 per pound) and an appropriate combination of high optical transparency and easy processing conditions. This polymer also showed the most promising properties for immediate use with a small amount of modification, but without extensive development efforts.

Table 1 presents the potentially suitable grades of EVA available on a commercial basis. Only two U. S. suppliers currently exist, DuPont Chemical Co. and United States Industrial Chemicals Co. (USI). The compounds of interest may be selected using transparency as the first criterion. Ninety-one percent transmission values are found for DuPont's Elvax 150, 250, 4260, 4320, 4355 and USI's EY902-30. Of these the acid modified terpolymers were eliminated due to the melt flow values being too high (Elvax 4320) or too low (Elvax 4260 and 4355) and additionally the cost, being around \$0.10/lb. higher than most other grades.

The EVA copolymer finally selected to investigate feasibility was Vynathane EY902-30 (U. S. Industrial Chemicals). The gum stock is readily compounded by two-roll milling, may be calendered or extruded into sheets at low temperatures,

and softens (ASTM E-28) at about 110°C. The melt index is approximately 70 g/10 minutes indicating low melt viscosity.

Aliphatic peroxide cure systems were investigated to give high transparency, low scorch with long processing times, and rapid cure at elevated temperatures. Aliphatic additives were employed to avoid the introduction of UV-absorbing species that might promote degradation. Aromatic compounds conventionally used for crosslinking EVA (triallyl cyanurate, dicumyl peroxide, Vulcup-R, etc.) are known to be UV absorbers and could possibly promote instability to weathering.

Laboratory experiments in sheet extrusion revealed that Vynathene EY902-30 gave excessive surface tack and uneven extrusion. It is likely that roll take-up of extruded Vynathene EY902 would be difficult due to its aggressive adhesion when still hot (50-60°C) from the extruder die. This material also "blocks" badly, making two sheets in contact with each other extremely hard to separate.

Due to these handling problems, a more suitable grade was selected from the wide range of EVA copolymers commercially available.

Of the two grades of Elvax remaining with high transmission (91%), Elvax 150 was selected over the 250 after conducting trial extruder runs in the laboratory to assess the processability of the formulated resin. Elvax 150 is a more desirable polymer for the reason of lower extrusion temperatures required due to its higher melt index. The Elvax 250 generated much more heat of shear during the extrusion process that could possibly degrade the peroxide content and lower the shelf life and curing efficiency of the compounded resin.

Two preliminary formulations were developed using Elvax 150, a clear compound to cover the sunlit side of the cell and a pigmented white compound to be used as a reflective background behind the cell. The trial formulations of these two compounds, designated EVA-2 and EVA-2W (indicating clear and white, respectively) are shown as follows:

| <u>Compound</u> | <u>Function</u> | <u>EVA-2^(a) Clear (Parts)</u> | <u>EVA-2w^(a) White (Parts)</u> |
|-------------------------------------|-----------------|--|---|
| Elvax 150 | Resin | 100 | 100 |
| Sartomer SR-350 | Crosslinker | 3.0 | 3.0 |
| Lupersol 101 | Initiator | 1.5 | 1.5 |
| UV-531 | UV absorber | 0.25 | -- |
| Trinuvin 7770 | UV synergist | 0.10 | -- |
| Irganox 1076 | Antioxidant | 0.50 | -- |
| Kadox 15 (ZnO) | Pigment | -- | 5.0 |
| Titanox RF-3 (TiO ₂) | Pigment | -- | 2.0 |
| Ferro AM-105 | Stabilizer | -- | 0.5 |

(a) These were the first fully developed compounds containing stabilizers, antioxidants and curing agents. (Notebook No. A8326)

These components were compounded on a two-roll mill for a total of 20 minutes at room temperature (25°C). The curing characteristics of the resulting elastomer were determined by solubility/gel fraction in toluene of specimens exposed to various time/temperature combinations. The attached graph depicts the approximate cure curve (Figure 1). As may be seen, the polymer is almost indefinitely processable up to about 110°C, but cures rapidly at 140-150°C.

Actual experiments in module building have shown that satisfactory cures are developed only at the higher temperatures (in excess of about 130°C) and that the cure mechanism is inhibited by air. The gel contents (degree of crosslinking) also vary somewhat according to cure conditions. The white stock averaged 50-60 percent by weight gel and the clear formulations 60-80 percent. This indicates that the pigment also has some inhibitory effect on cure.

Compression-molded specimens were evaluated for physical properties after 20-minute cure at 150°C, with the following results:

| <u>ASTM-D638</u> | <u>EVA-2 (Clear)</u> | <u>EVA-2W (Pigmented)</u> |
|--|--------------------------|-------------------------------|
| Tensile strength, psi | 1890 | 1710 |
| Ultimate elongation, % | 570 | 580 |
| Secant modulus, psi (100% elongation) | 360 | 360 |

After 24 hours at 90°C no creep could be noticed in the sheet specimens hung vertically.

These preliminary formulations provided a baseline compound from which further studies of EVA performance could be conducted. Module fabrication techniques were also under development at the same time to determine the best process for encapsulating cells with the new potting compounds. Fabrication techniques will be discussed in a subsequent section.

With the background of fabrication experience provided by the preliminary formulations, it becomes possible to reformulate the EVA to yield a better compound. Some of the properties that needed improvement included:

1. Lower temperature cure.
2. Faster cure, shorter time.
3. Fewer ingredients, if possible.
4. Lowered content of volatile components to reduce bubbling under heat and vacuum.
5. Optimized UV stabilization system.
6. The possible incorporation of compounds such as silane primers to improve the adhesion to substrate or superstrate surfaces.

b. Curing Agents/Peroxide Selection

Conventional formulas for crosslinking EVA frequently employ a co-crosslinking agent, either triallyl cyanurate or SR-350 (trimethylol propane trimethacrylate). It was discovered that with Elvax 150 polymer, better cures are obtained without this agent. EVA-3 (clear) with no SR-350, gives comparable gel of 90%, and white EVA-3W with no SR-350 went up from 55% to 75% gel content under the same cure conditions.

In addition to improving the speed and degree of cure, the elimination of the SR-350 is advantageous because it removes the large quantity of a volatile component that may contribute to bubble formation during the vacuum bag processing step.

Ethylene vinyl acetate copolymer has been compounded in large quantity without any SR-350 crosslinking agent and has also been extruded on a pilot plant scale to yield a sheet of 30 inch width for experimental encapsulation studies. The revised formulations are as follows:

| | <u>EVA-3 (clear)</u> <u>parts</u> | <u>EVA-3W (white)</u> <u>parts</u> |
|--------------|--------------------------------------|---------------------------------------|
| Elvax 150 | 100 | 100 |
| Lupersol 101 | 1.5 | 1.5 |
| UV 531 | 0.25 | - |
| Tinuvin 770 | 0.10 | - |
| Irganox 1076 | 0.50 | - |
| Kadox 15 | - | 5.0 |
| Titanox RF-3 | - | 2.0 |
| Ferro AM-105 | - | 0.5 |

It was noticed during the extrusion process that the screw and barrel temperature rose to about 245°F from the heat of shear. This increase is due to the absence of the SR-350 which plasticized the resin and lowered its melt viscosity. This was not expected to present a problem with the clear formulation; however, it had a significant effect on the white formulation. The white compound extruded with very inadequate mixing of the pigments. The ingredients were poorly dispersed and came out of the extruder in small lumps which could be broken into powder between the fingers. Only translucent streaks of pigment appeared in the body of the polymer. It appears that the SR-350 served as a dispersing agent and

a flow modifier for the adequate blending pigment. An approach to solving this problem was to masterbatch the pigment into a small amount of polymer on the mill roll or some other high shear mixing device and then blend it into the final formulation as pellets. This has the advantage of high shear mixing at high temperature without degradation of the peroxide which is blended with the other portion of the resin.

An additional approach to the problem of reducing the heat of shear developed in the extruder was to use a water cooled screw or barrel, thereby permitting the resin to be worked harder without the degradation of the peroxide that occurs with higher (122°C) temperature.

Further investigation was then conducted into the nature of the peroxide curing system. Experiments have shown that the polymer may be cured to a 95 percent gel content with 0.5^(a) phr of Lupersol 101 peroxide, one-third the quantity used in the original formulation. The relationship between gel content and thermal creep resistance was explored. Low levels of peroxide were used to give a range of gel content polymers which were subsequently cured into slabs of 3" x 1-1/2" x 0.5" thickness. These slabs were then hung vertically in a circulating-air oven at 100°C for 120 hours. Thermal deformation became noticeable at 53 percent gel, indicating that the cure system should generate crosslinking in excess of this value.

Other aliphatic peroxides were screened for the curing of EVA at the 0.5 phr level. The only three that worked are listed as follows with the resulting gel contents:

| Peroxide | Cure Conditions | | | | | |
|------------------|-----------------|------------------|------------------|-----------------|------------------|------------------|
| | 150°C 5 min. | 150°C 10 min. | 150°C 20 min. | 135°C 5 min. | 135°C 10 min. | 135°C 20 min. |
| Lupersol 101 | 0% | 0% | 92.9% | 0% | 0% | 0.4% |
| Lupersol 231 | 91.5% | 91.9% | 92.7% | 0% | 79.8% | 92.9% |
| Lupersol 220-D50 | 92.6% | 93.2% | 83.8% | 0% | 0% | 84.6% |

No curing occurred below a temperature of 120°C at any length of time.

The results indicate that as little as 5 minutes cure time at 150°C may be feasible using other peroxides, or that the usual 20 minutes cure time may be used at a temperature of only 135°C. Lupersol 231 (1,1-bis(t-Butyl peroxy) 3,3,5,-trimethyl cyclohexane) appears to be the best suited peroxide for EVA, if it proves to be compatible with the other additives, especially the antioxidants.

(a) phr; Parts per hundred parts resin.

The results of a more extensive investigation are shown in Table 2 (Appendix). Lupersol 101 and Lupersol 231 were compared for cure efficiency by gel content in a typical EVA formulation incorporating UV stabilizers and an antioxidant. Both Elvax 150 and 250 were used in this experiment to further compare the usefulness of the resins. The results indicate that Elvax 150 is much more successfully cured than the 250 and that Lupersol 231 appeared to be the peroxide of choice for this application.

However, severe problems were encountered when modules were constructed with this formulation. All modules (both 2 cell as well as 11 cell minimodules) fabrication attempts resulted in the pottant layer filled with bubbles. These bubbles were small in size and uniformly distributed throughout the pottant. No variation in time/temperature/pressure profile resulted in any improvement. A range of formulations were prepared to determine if one of the other ingredients was having an antagonistic effect on the peroxide and giving rise to the bubble problem. The peroxide alone was found to be responsible for the difficulty. Slower heating rates during module fabrication did not improve the quality. No variation of the technique resulted in bubble free modules. The decision was made to return to the original Lupersol 101 peroxide. The potential for bubbling of candidate pottants was assessed as follows:

c. Compound Degassing

An experiment was conducted to measure and compare the bubbling of pottant materials to give a quantitative comparison. This was done by foaming a specimen of the pottant in a vacuum oven at the fusion temperature and measuring the amount of foam by the resulting decrease in specimen density. The following table gives the results.

| <u>Degassing Experiment</u> | | | | | |
|-----------------------------|-------|-------------------|-------------------|---------|-----------|
| Compound | PVB | A9918 | A9906-C | A9903-B | Elvax 150 |
| Composition | SR-10 | EVA + Lup. 101 | EVA + Lup. 231 | White | Uncomp. |
| Density, before (g/cc) | 1.076 | 0.961 | 0.959 | 0.985 | 0.945 |
| Density, after (g/cc) | 1.099 | 0.950 | 0.891 | 0.989 | 0.955 |
| % Change | +2.14 | -1.14 | -7.09 | +0.41 | +1.06 |

As can be seen from the percentage of change in the bottom line of the table, the formulation based on Lupersol 231 showed the greatest reduction in density and consequently the greatest amount of bubbling, approximately six times that of the clear pottant formulation using Lupersol 101 as the curing agent. Due to this difficulty Lupersol 101 peroxide was used for subsequent formulations.

d. Antioxidant selection

Antioxidants are generally used in rubber formulations to improve the color and mechanical property stability and extend the useful life of the material.

With the return to Lupersol 101 peroxide, it was decided to perform a series of experiments to select an improved antioxidant. Formulations were prepared with different candidate antioxidants and molded into cured plaques that were subsequently heat aged in a circulating air oven. Each plaque also contained a disc of unprimed copper to examine any corrosion effects that might occur. The compounds were evaluated for cured gel content, gel density (tight or loose cure), color upon thermal aging and corrosion effects on the copper disc. Table 3 records the results. The compounds that could be rejected immediately were those with low gel contents indicating insufficient cure.

The antioxidants were compounded into a complete formulation to include any antagonistic effects that could occur from other ingredients. A slightly lower level of peroxide (0.75 phr) was used to accentuate the free radical inhibition effect of the antioxidant (Table 3).

The best overall performance was found for Naugard-P. This compound gave high gel contents, no corrosive attack to the copper disc.

After 90 hours at 90°C the polymer specimen showed no signs of color formation and no ring could be seen around the copper disc. The thermal aging has been continuing and, to date, the test specimens have been exposed to over 400 hours of 90°C. No further changes have been observed. A distinct advantage to the use of Naugard-P is that it is not a phenolic compound and, therefore, does not give rise to UV sensitization and possible degradation of the polymer. Chemically, Naugard-P is an alkyl aryl phosphite, a high viscosity transparent fluid.

An identical set of experiments was previously run with the Lupersol 231 peroxide. None of the polymers/antioxidants performed as well as the Lupersol 101 formulations, all being equivalent to a color index of 2 to 3 on the chart (Table 3) and with noticeably more corrosion. It appears that the Lupersol 231 cure yields polymers that are less easily stabilized. Current EVA formulations employ 0.2 phr of Naugard-P as the antioxidant.

e. Compounding and Extrusion

Any material to be used in the construction of solar modules must first have the required physical, thermal, optical, and electrical properties; but second must be available in a form that is amenable to fabrication. In order to use polymeric materials as pottants, it is necessary that the physical form of the polymer be appropriate to the encapsulation technique being employed.

Plastics are commercially available in four basic forms: liquid, pellets, powder, and bulk (chunk). Some polymers are restricted to handling in a specific manner, others may be converted to more useful forms suited to the particular application. Ethylene/vinyl acetate is a versatile polymer that is manufactured in pellet form but may be converted to other forms such as liquid (injection molding) or sheets (extrusion). The sheet form has been found to be the most useful to date and is suited to a wide variety of lamination techniques.

Preliminary investigations of the conversion of EVA copolymer into a useful precompounded sheet form were conducted on a small scale in the laboratory using a Brabender "Plasticorder". This device consists basically of an electric motor, a gear reduction unit, and a miniature single-screw extruder attachment. This equipment was used to determine the basic extrusion conditions for the clear (EVA-2), and pigmented white (EVA-2W) EVA compounds (see initial formulation section for formulations).

The temperature profile, back pressure, and screw speed were determined initially with the "Plasticorder" adapted to a 3/4 inch diameter extruder with a 6 inch width film die. All three compounds were found to extrude easily at die temperatures of only 75-80°C. The die back pressure remained fairly constant at 1600 psi and the screw speed was maintained at 60 rpm. The extruded sheet was very clear and manageable; however, the thickness was variable and could not be set precisely using the particular die construction in use.

The preliminary conditions established in the laboratory were then used towards a large-scale pilot plant production. A major extrusion effort was conducted using a Hartig 2-1/2 inch extruder with a two-stage screw containing a mix zone for resin blending.

Large amounts (200-300 pounds) of both clear and pigmented compounds were prepared by ribbon blending and were run directly into the extruder hopper. The highest temperature used was 95-100°C at the mix zone and 75°C at the die. The back pressure was 2400 psi for the clear formulation (EVA-2) and about 3000 psi for the white compound (EVA-2W).

The following lists the average extrusion conditions found for both resins:

EVA Extrusion Conditions

Equipment: Hartig 2-1/2 inch extruder w/single stage polyethylene screw.
Screw compression ratio; 3.5:1, Water cool option.
Screen Pack: 20, 100, 80, 20 Mesh
Die width: 32 inches----full web.

Temperature Profile:

| Zone | BARREL | | | | | | DIE | | | |
|--------------|--------|-----|-----|-----|-----|-----|-----|-----|-----|----------------|
| | 1 | 2 | 3 | 4 | 6 | 8 | 9 | 10 | 11 | |
| Set Temp. °F | 190 | 200 | 200 | 175 | 175 | 175 | 175 | 175 | 175 | |
| Run Temp. °F | 200 | 205 | 205 | 210 | 175 | 175 | 175 | 175 | 175 | EVA-4 - clear |
| Run Temp. °F | 200 | 200 | 210 | 220 | 180 | 180 | 180 | 180 | 180 | EVA-4W - white |

Take up rolls: Roll No. 2 - 80°F - Rolls 3, 4 approximately 60°F.

Back Pressures: 2600 psi (EVA-4 - clear) 2650 psi (EVA-4W-white)

Screw speed: 36 rpm (22%)

Speed, Extrudate: 6.4 - 6.5 feet/minute, 32 inch width: approximately 110 lb/hr.

Thickness: 18 mils \pm 1 (clear), 14 mils \pm 1 (white)

Extrusion proceeded smoothly with no difficulties. Slow water trickle through screw appeared to be effective in maintaining the temperature below 225°F (108°C).

The sheet was extruded at a rate of about 8 feet per minute and was taken up on chrome rollers cooled to 5-10°C. The thickness was uniform across the 24 inch wide sheet at 0.018" \pm 0.01". The sheets were wound on cardboard cores with release paper interleaving. The interleaving is necessary to prevent the wound sheet from "blocking" or sticking to itself so that the plies are difficult to separate. In future studies, embossing of the sheet (similar to polyvinyl butyral safety glass sheet) may be found sufficient to prevent this blocking and may also aid in de-airation during fabrication. Alternatively, a light coating of an absorbable release powder such as silica might work.

The sheet quality was excellent and no cure advancing of the resin was found to have occurred. Blending of the ingredients was found to be uniform in both formulations, however, a different compounding procedure had to be used for the pigmented compound.

The clear EVA compound is easily prepared by taking the ingredients as listed in the formulation and simply tumble blending them in a rotating drum. The liquid ingredients disperse over the surface of the EVA pellets in this process and cause the powdered ingredients to adhere in a uniform layer. After half an hour of tumble blending the resulting mix can be used directly as "hopper feed". No inhomogeneity can be noticed in the final product and the extrusion process yields a thorough blend.

The pigmented formula requires a special compounding operation and a number of experimental extrusions were run before a successful process was discovered. Simple tumble blending as is done for the clear compound is ineffective, giving rise to streaks and chunks of undispersed pigment throughout the surface of the film. The results had been better in a prior formulation in which the SR 350 cross-linking agent had been included which suggested that the incorporation of an appropriate dispersing agent might solve the problem. The addition of a silane (Z-6030/Z-6020,9:1) ^(a) did not appear to help when added at a level of 1 phr ^(b) and the extruded sheet was still speckled with small chunks of unblended powder. Despite the persistent lack of pigment dispersion, all other ingredients appeared to have blended. Gel contents of 70% or better were found after the standard cure test.

The compounding problem was finally solved by preparing a "masterbatch" of the pigment in a small amount of polymer and then blending it with the bulk of the formulation prior to extrusion.

The formulation in total consisted of the following ingredients:

| EVA-4WT (Final, Pigmented) | |
|-------------------------------|--------------|
| | <u>Parts</u> |
| Elvax 150 | 100 |
| Lupersol 101 | 1.5 |
| Kadox 15 Zinc Oxide | 5.0 |
| Ferro AM 105 | 0.5 |
| RF-3 Titania | 2.0 |

(a) Silanes, Dow Corning Corporation

(b) phr; Parts per hundred parts resin

It should be noted that in order to increase the opacity and reflectivity of the film titanium dioxide pigment was included (the "T" suffix). This component was originally excluded on the basis that some grades of titania appear to give rise to UV sensitization and subsequent degradation of their resin vehicles. This is true for anatase grades, however, and not the rutile grades. A rutile grade was selected for incorporation at the 2.0 phr.

The AM-105 is included in the masterbatch because it is also very difficult to compound by extrusion.

The masterbatch was prepared on a two-roll differential mill at room temperature and consisted of the following:

| <u>EVA-4WT</u> Masterbatch | |
|-------------------------------|--------------|
| | <u>Parts</u> |
| Elvax 150 | 25 |
| Kadox 15 | 50 |
| Ferro AM 105 | 5 |
| RF-3 Titania | 20 |
| | <u>100</u> |

The masterbatch compound was then cut into "hopper feed" using a rotary blade mill after freezing the compound in liquid nitrogen. Extruder stock was prepared by blending correct amounts of the masterbatch with Elvax 150 and Lupersol 101 peroxide in a tumble blender. The resulting product was then run directly into the extruder, which produced a good quality thoroughly blended film. The equipment, temperatures and other particulars of the extrusion runs are the same as those indicated in the extrusion conditions previously reported.

f. Ultraviolet Stabilization

Only acrylics, silicones, and fluorocarbons are inherently resistant to weathering. This limitation does not mean that plastics cannot be modified for outdoor use, however. Weather-resistant coatings or internal compounding of special additives can achieve dramatic improvements in environmental resistance.

The deterioration of plastics in outdoor weathering is caused primarily by sunlight - especially ultraviolet - frequently combined with atmospheric oxygen

and often involving moisture, abrasion, and other factors as well. Sunlight reaching the earth is filtered through the atmosphere, removing shorter wavelengths up to 290 nm before it reaches the surface of the earth. Thus ultraviolet effects on plastics result primarily from wavelengths of approximately 290-400 nm, which is approximately 5 percent of the total solar radiation reaching the earth.

In general, ultraviolet energy initiates breakdown by dissociating a covalent chemical bond into a free radical. This initiates a free-radical chain reaction. In the presence of atmospheric oxygen, this usually becomes an oxidative chain reaction. Formation of degradation products like C = O and C = C double bonds, and hydroxyl O - H and peroxide O - O groups increases the number of groups which can absorb ultraviolet light and thus accelerates the degradation reaction.

These chemical modifications of the polymer are responsible for the deterioration of optical and mechanical properties and usually result in reductions of tensile strength, elongation, and transparency.

Protection from UV light is obtained with stabilizers known as ultraviolet absorbers and quenchers; protection from oxidation is achieved with the use of antioxidants. Most frequently the two used together have a synergistic reaction in which the increase in weatherability is greater than that obtained with the use of either one alone.

The absorbance ability of a group of common UV absorbers is shown in Figure 12.

The absorption of ultraviolet light may or may not result in polymer degradation, depending on how this energy is dissipated. If the absorbed energy is converted to heat or a longer wavelength (fluorescence), no adverse effects may be observed. If the absorbed energy results in chain scission or chemical rearrangement, degradation will occur. Polymers affected in this manner must be protected from ultraviolet to prevent decomposition.

An additional problem inherent in UV stabilization is compatibility, as is demonstrated by the two systems below. Formulation A is Compound EVA-3 and gives no color after heating in the mold at 150°C for two hours. However, when Tinuvin 327 is substituted for Cyasorb UV 531 in formulation B, the sheet yellows after two hours of heating.

| | <u>A</u> | <u>B</u> |
|---|----------|----------|
| Elvax 150 | 100 | 100 |
| Lupersol 101 | 1.5 | 1.5 |
| Tinuvin 770 | 0.1 | 0.1 |
| Cyasorb UV531 | 0.3 | - |
| Tinuvin 327 | - | 0.3 |
| Irganox 1076 | 0.2 | 0.2 |
| Color after mold- ing 120 min. at 150°C | OK | Yellow |

The compatibility of polymer additives and the net resulting increase in stability is best determined by an empirical approach of screening formulations and observing the relative stability of each. An accelerated method of exposure - the RS/4 sunlamp - is used for this purpose.

Materials of interest were subjected to RS-4 fluorescent sunlamp exposure for a period of 5 months (4000 hrs) to indicate the relative stability of each to intense UV radiation. Although the results of this exposure series are subjective in nature, useful information is obtained about the relative stability of various formulations. The following gives the results:

- A. Elvax 150, control Transparent, colorless, very tacky, soft and cheesy.
- B. Elvax 150, cured with Lupersol 101, no stabilizers.
Transparent, very slight yellow color, tacky surface, soft but higher in tensile strength than A.
- C. EVA-2, cured and stabilized.
Transparent, very light yellow, tough resilient and rubbery, no surface tack, slight haze.
- D. EVA-2W, white. Tough, resilient, no surface tack, slight yellowing of surface.
- E. EVA-1, unstabilized, cured between two pieces of Korad 201-R.
Unaffected, no apparent change in mechanical properties, very slight haze to surface.
- F. EVA-1, unstabilized, coated with National Starch 42A acrylic UV absorbing solution.
Clear, transparent, coating in good condition, underlying polymer appears to be well protected, no discoloring.
- G. EVA-1, unstabilized, cured between two pieces of soda-lime glass, SS4179 primer.
No apparent change, no bond failure.
- H. EVA-1, unstabilized, cured between glass and Korad 201-R, SS4179 primer to glass.
No signs of degradation of any kind, but bond failures.

- I. EVA-1, unstabilized, coated with B-48N acrylic solution containing UV absorbers.

Specimen rolled up, coating fractured, underlying polymer soft tacky and degraded.

- J. Super-Dorlux No apparent change (color, surface delamination)

A small piece of EVA-2 (cured with Lupersol 101, Sartomer 350 and Irganox 1076) has survived over 4000 hours of RS/4 exposure. Mechanical tests were run on a small piece and gave the following results:

| | <u>EVA-2</u> | <u>Unexposed Control</u> |
|---------------------------|--------------|------------------------------|
| Tensile strength | 1800 psi | 1890 psi |
| Ultimate elongation | 570 % | 570 % |
| Stress at 100% elongation | 360 psi | 360 psi |

The results are almost identical to the unexposed compound, indicating excellent stability.

In summary, a commercially available grade of ethylene-vinyl acetate copolymer has been found that appears to have many of the desired properties for a solar module encapsulating compound. High optical transmission, low melt temperature, low melt viscosity, ease of compounding and low cost all lead to a promising material. The grade selected for development has been successfully compounded to give a composition that may be extruded into sheet form with ease at a low temperature and subsequently cured to a creep resistant rubber at a higher temperature. The feasibility of compounding, extruding and handling pilot plant quantities of this formulation has been demonstrated and module fabrication attempts have been successful (following sections).

Although no conclusive statement can be made concerning the weatherability or outdoor lifetime of this polymer, studies involving indoor accelerated aging techniques suggest excellent stability to ultraviolet light, the most deleterious component of outdoor weathering. Correlations with outdoor exposure are being evaluated under other phases of the LSA program.

IV. MODULE FABRICATION ATTEMPTS

This section describes the early attempts at encapsulation with ethylene-vinyl acetate that resulted in failure, and is included here to document the trial and error experiences that preceded the development of a successful method. Module manufacturers and other EVA users will hopefully benefit from knowledge of these initial experiments. Several approaches to module fabrication were attempted, the object being to encapsulate the cell by a fast, reproducible process that did not damage the cell or incorporate bubbles, voids, or any other defect that could serve as a locus for failure. All the techniques attempted were variations of a process employing heat to fuse the EVA pottant and vacuum to remove trapped air and bubbles.

Standard fabrication test modules were constructed measuring 3" x 3" (7.6 cm x 7.6 cm) and containing one solar cell (57 mm diameter); these were used throughout the range of experiments with only minor variation.

Simple laminates were prepared by assembling layers of the raw materials composing the encapsulation package. For substrate-based designs these laminates consisted of 3" x 3" (7.6 cm x 7.6 cm) squares of the following materials in order, from topside to underside:

- Clear EVA (formula EVA-1) ^(a)
- 57 mm Diameter Solar Cell, Active, Face Up
- Clear EVA (formula EVA-1)
- White EVA, (formula EVA-1W)
- Super-Dorlux, Vacuum Dried

For superstrate designed modules, the materials consisted of, from top to bottom:

- Soda-Lime Glass, Primed
- Clear EVA (formula EVA-1) ^(a)
- 57 mm in. Diameter Cell, Face up, Active
- Clear EVA (EVA-1)
- White EVA (EVA-1W)

(a) EVA-1 is a formula for compounded EVA containing only curing agents, but no UV stabilizers. This compound was used for initial fabrications in order to provide specimens for degradation studies.

The lamination processes attempted with the preassembled modules went through a number of changes before evolving to a viable encapsulation method. The processes used and the modifications made are described as follows:

A. Vacuum Oven

The first technique tried was that of simply placing the preassembled module into a preheated vacuum oven and permitting the module to come to fusion temperature (approximately 60°C) under evacuation. The vacuum step is necessary, as modules fused in a circulating-air oven fuse with large amounts of trapped air.

A full vacuum of 30 in. Hg was applied to the oven immediately after loading the module and the fusion temperature was reached in about half an hour.

Laminates prepared in this manner failed due to bubbling and blistering of the molten resin. The highest temperature obtainable before the onset of this difficulty was found to be 70°C \pm 5°. Single sheets of EVA responded in the same manner indicating that in part the degassing was also a property of resin composition. Increases in temperature to 90 or 100°C made the situation worse. Modules removed below the 70°C temperature were poorly fused with irregular surfaces, some large bubbles of entrapped air and poor appearance. Variations in the time-temperature-pressure profile brought no improvement.

B. Vacuum Fusion-With Backfill

In an attempt to reduce the degassing and inhibit bubble formation, the vacuum oven was operated at full vacuum until primary fusion had taken place at about 70°C and was then backfilled with nitrogen to ambient pressure. Nitrogen was used as the backfill gas because the oxygen component of air tends to inhibit the cure of peroxide crosslinked systems. It was expected that the increase in pressure at the fusion point would solve the bubble problem by reducing the vapor pressure of the resin, however, no success resulted from this approach. The highest temperature attainable was 80°C, at which point the onset of irreversible bubbling occurred again. Additional problems included the absence of cure (due to low temperature), cell shifting, and excessive loss of resin over the edges of the substrate.

C. Vacuum Pack

In order to take further steps towards the suppression of bubbles, a direct contact approach was tried. Positive pressure was applied directly to the surface of the module by assembling a sandwich "pack" of sheet materials around the module. Varying pressures were then applied to the assembly by placing weights on the top surface. The "pack" consisted of the following assembly:

| | |
|-----------------|-------------------------------------|
| Top Section: | Weight |
| | Aluminum support plate, 6"x6"x1/16" |
| | Cardboard, 6"x6"x1/8" |
| | Silicone rubber, 6"x6"x1/32" |
| | FEP film, 3"x3"x0.01" |
| Middle Section: | Cell lay-up, as in (A) |
| Bottom Section: | Cardboard, 6"x6"x1/8" |
| | Aluminum, 6"x6' x1/16" |
| | Cardboard, 6"x6"x1/8" |
| | Aluminum plate, 6"x6"x1/16" |

Each material was included to provide a specific function.

The FEP film was placed over the module surface to serve as a release surface, the cardboard served to slow down the heat transfer, allowing a longer evacuation time (before fusion); and the aluminum plates serves as rigid support members. The final assembly was taped over the edges to prevent the assembly from shifting.

Loading this pack into the vacuum oven with 0.2 to 0.5 psi (resultant weight on the 3"x3" module surface) pressure resulted in much improved modules with flat surfaces. The limiting temperature was found to be approximately 70°C, as before. Up to this temperature modules could be produced entirely bubble-free, well fused, and of good appearance. Above 70°C degassing began, again resulting in bubble inclusions, although not quite as severely as previously.

The module inside the pack assembly is estimated to reach 70°C in about 45 minutes in the vacuum oven.

The main problem remaining was still that of raising the module to a sufficiently high temperature to cure the EVA encapsulant without the destructive degassing.

The pottant in the modules produced by any of the preceding processes was found to be uncured and completely thermoplastic. Curing does not appear to occur at 70°C - 100°C regardless of how long the resin remains at temperature (see cure curve, Figure 1).

D. Vacuum Pack with Backfill

A combination of the preceding methods was tried. The module "pack" assemblies were fused under full vacuum to a temperature of 70°C and the oven backfilled with nitrogen to ambient pressure as before. The temperature was then raised to 150°C for an additional period of two hours and the modules removed. About 20% of the modules resulting from this process were well fused, bubble-free and showed no signs of cell damage. The remainder were failures and although they had some bubbles, failed more from excessive resin exudation (loss of encapsulant) than any other difficulty. Additionally, the pottant had low levels of cure. Although the polymer was found to cure well in a compression mold at 150°C, vacuum packs at the same temperature showed almost no crosslinking. This is thought to be due to slow and ineffective heat transfer causing the peroxide to decompose before the cure temperature was reached.

E. Vacuum Pack-Air Oven

Successfully fused and bubble-free modules prepared by procedure (C) were left in their pack assemblies and cure was attempted in a circulating oven. Loading into an oven directly at the desired 150°C resulted in the usual bubbling problem, so a more gradual approach was taken. Module packs were removed from the vacuum oven at 70°C and placed in an air oven at 80°C. The temperature was then raised 10°C every 1/2 hour until 150°C was reached. Most modules survived well, with only 20% (approximately) failure rate due to bubbling and degassing. Despite adequate time for equilibration at a sufficiently high temperature, the cure of the EVA was still found to be marginal at gel contents of 10-20%. These modules did not survive temperature cycling at 90°C and flowed to destruction.

These results suggest that the presence of air inhibits the high temperature cure, even in a pack lay-up; and that a rapid heat transfer may be necessary to overcome inhibition effects. Thermal decomposition of the peroxide at temperatures below those required for crosslinking may also be the cause of low gel contents.

F. Autoclave

A few experiments were run with a miniature laboratory scale autoclave that could be pressurized with nitrogen.

Superstrate cell lay-ups with no pack as described in (A) were placed in a preheated autoclave at 120°C and immediately evacuated to 30" Hg. After a length of time under vacuum to remove entrapped air, the autoclave was backfilled with nitrogen to a pressure of 280-300 psi and left for half an hour. The idea was to

backfill at the onset of fusion and suppress bubble formation with the high pressure atmosphere. Modules pressurized after 5, 10 and 15 minutes of vacuum still gave poor results with bubbling and degassing of the EVA.

Throughout the six approaches summarized so far, the following problems were encountered:

- (1) Bubble formation - occurring in all cases except (E).
- (2) Incomplete cure - occurring in all cases.
- (3) Lack of adhesion - occurring in most cases.
- (4) Severe resin flow and cell shifting.
- (5) Pigmented resin overlapping cell surface - partially solved by using lightly precured pigmented resin.

A fabrication method is therefore required that prevents air inhibition of the resin cure system, holds the module components physically in place and applies a pressure to the system to insure rapid heat transfer and suppression of bubbling.

V. VACUUM-BAG FABRICATION

A successful and reproducible module fabrication technique was finally achieved using a vacuum bag. The "Bag" consisted of an aluminum picture frame supporting a flexible silicone rubber diaphragm. This frame was then placed on a solid aluminum support plate covered with a thin layer of grease and the whole assembly evacuated through a piece of tubing in the side of the frame. (See Figure 2). Module lamination was achieved by assembling a "lay-up" of materials as before: (superstrate example)

| | |
|-------------------------|---------------------------|
| FEP Film | - release film |
| Pigmented EVA | - reflective rear pottant |
| Clear EVA | - transparent pottant |
| Solar Cells (Face Down) | |
| Clear EVA | - Transparent pottant |
| Soda-Lime Glass | - superstrate |

This assembly was then placed between the support plate and the diaphragm held on the picture frame. Applying the vacuum (30 in. Hg) resulted in removal of air trapped between the sheets of encapsulant and also compressed the assembly to 14.7 psi from the action of the diaphragm. While under vacuum, the entire vacuum bag was loaded between the preheated (150°C) plattens of a hydraulic press which served as the heat source. The ram pressure was just sufficient to close the press and insure good heat transfer to the vacuum bag. The time required for adequate fusion and cure was determined by placing a micro thermocouple over the module assembly. Twenty minutes of cure time was allowed after a temperature of 140°C is reached. Samples of encapsulant from modules prepared in this manner show adequate cure and gel contents in excess of 75%. A graph of the time-temperature-pressure cycle is attached, see Figure 3.

It is necessary to mention that the edges of the module lay up were sealed with masking tape prior to loading to prevent the EVA polymer from filling the inside of the vacuum bag. Although the edges were securely taped, entrapped air appears to diffuse through with no difficulty under evacuation.

Solar Power Corporation has recently used this technique to prepare glass-superstrate modules of 11" by 15" dimensions and containing 11 electrically active cells. These modules are fully cured, bubble free, of good appearance and

show no cell damage. Additionally the use of recently discovered General Electric SS-4179 primer resulted in excellent adhesion. Glass/EVA specimens using this primer have survived three weeks of water immersion with no signs of delamination. Dr. Edwin Plueddeman of the Dow Corning Corporation under contract to JPL has also discovered effective primers for bonding EVA to glass that are water resistant^(a).

Springborn Laboratories concentrated on the vacuum bag fabrication of one-celled modules to be used in accelerated degradation experiments (see Figure 4) and Solar Power Corporation (under subcontract) constructed most of the large multi-celled modules (see Figure 5). The modules produced by this method were of two types: superstrate with soda-lime glass, and substrate on Super-Dorlux. Both constructions were of good quality, well fused, crosslinked, and almost bubble-free. One special module was prepared with a cover of Korad X201R acrylic film as an integral part of the encapsulation process (see Figure 6).

Using the vacuum bag concept, a further improvement of the module fabrication process resulted. The apparatus was modified by including a top cover and an additional hose fitting (see Figure 7). This adaption enabled both cavities above and below the flexible diaphragm to be evacuated. The advantage to this modification is that it is possible to keep the module assembly under direct and full vacuum while the pressure from the diaphragm of the top surface may be varied from zero to full atmospheric pressure (30 in. Hg). The pressure resulting on the surface of the module can also be changed with time and temperature to avoid excessive loading of the cells when the pottant is still too inflexible to provide stress relief. This "double vacuum bag" process yields improved modules with fewer defects such as cell cracking, bubbles and irregular surfaces and provides greater control over the time/temperature/pressure cycle thereby giving greater control over the fabrication process.

It was discovered empirically that the best results were achieved when full evacuation of the top cavity is continued until a fairly high temperature is reached (approximately 120°C) during the cure cycle. At this point the vacuum is slowly released and the diaphragm puts the module into compression.

In previous work, the top cavity was returned to ambient pressure upon the beginning of the cure cycle, thereby putting the module in compression before the resin had reached the melt stage. With the new technique the pressure of the diaphragm is applied to the surface of the module gradually over a 10 minute

(a) Plueddeman, E., "Chemical Bonding Technology for Terrestrial Solar Cell Modules" JPL Document 5101-132, Jet Propulsion Laboratory, Pasadena, California, September 1, 1979.

period when the resin is in a melt stage and, therefore, capable of supplying stress relief. Cell cracking appears to have been totally eliminated with this process because the cells are free to float in the resin during the compression stage and subsequent cure. The static load occurring in the fluid medium eliminates localized stresses that could appear on the cell surface. Bubbles also have been eliminated due to longer time available for degassing under a no-load condition. All large and small modules produced in this program will employ this technique. A graph of the temperature and pressure conditions versus time is shown in the attached Figure 8. The temperatures shown were determined with an iron/constantan thermocouple placed on the surface of the module throughout the vacuum bag process.

The fabrication steps followed in the double vacuum bag process may be summarized as follows:

- (1) Assemble the module construction materials as shown in Figure 9, including the FEP release film, the aluminum shim stock and the masking tape. Seal the edges firmly with the tape, making sure that the corners are covered.
 - (2) Place the preassembled module in the double vacuum bag chamber between the diaphragm and support plate (lower cavity).
 - (3) Evacuate the entire assembly (both cavities) through the side connections to a pressure of 29 - 30 in. Hg for a period of at least 10 minutes.
 - (4) With the vacuum still applied, place the vacuum bag assembly between the heated platens of a hydraulic press or any other heat source capable of making intimate contact.
- (NOTE: if a hydraulic press is used, the ram pressure should only cause the platens to close, but not compress the gaskets of the vacuum assembly.)
- (5) Permit the assembly to heat at a rate of approximately 4°C per minute until a temperature of 120°C is reached. This should take around 20 minutes.
 - (6) At the 120°C point the top cavity vacuum should be released slowly, so that the cavity returns to ambient pressure in 8 - 10 minutes.
 - (7) Continue the heating process until a temperature of 150°C is reached. The time between 140°C and 150°C should be approximately 10 minutes. This is the point at which most of the curing of the pottant occurs. Allow an additional 5 minutes at the 150°C point to insure that adequate heat transfer has taken place.
 - (8) Remove the heat source, and permit the entire assembly to cool with the vacuum still applied to the lower cavity.

- (9) The module may be removed whenever the assembly becomes cool enough to handle.

This process has been used successfully in the preparation of single celled laboratory modules of 4 x 4 inch size, double celled modules of 4 x 8 inch size and 11 celled modules of 11 x 15 inch size.

It should be emphasized at this point that heating rates are important in the fabrication of modules that are adequately cured and resistant to thermal deformation.

A module was prepared in the usual manner, except that the heating rate was lowered to about half that normally used. Instead of attaining 150°C in about 45 minutes, this module was insulated so that 150°C was reached in 90 minutes. A zero gel, or no cure condition resulted. This indicates that a cure schedule must be developed that specifies the minimum heating rate required to give acceptable gel content. If the heating rate is too slow the peroxide will probably undergo thermal decomposition and be depleted before the temperature required for cross-linking is reached.

Presumably the heating rate may be too rapid as well. If the polymer is brought to cure conditions too soon, it may have insufficient time to properly degas and bubble entrapment may occur. The precise cure rates will vary with changes in pottant formulation. The formulations are still in a process of evolution, consequently precise cure curves have not been determined yet.

The advantages found with this encapsulation method may also be briefly summarized, and are as follows:

- (a) Rapid fabrication, approximately 1-hour cycle
- (b) Free of bubbles and voids
- (c) Ease of materials handling
- (d) Good cure of the resin
- (e) Good adhesion (with the primers used to date)
- (f) No cell shifting
- (g) Minimal loss of encapsulant during fusion
- (h) No cell or interconnect damage
- (i) Potential for automation

The large 11 in. x 15 in. modules have successfully passed the JPL thermal cycle test, JPL document LSA 5101-65.

A brief cost analysis was conducted for both substrate and superstrate modules prepared by this method. Calculations were realistically based on actual measurement of the thickness of the pottant layer and determination of the amount of resin used. For a routinely prepared module, the total encapsulant profile was found to be in the order of 0.045 inch. This figure excludes the thickness of the substrate or superstrate.

After fusion, the module surface is quite flat and it is assumed that the pottant has become evenly distributed throughout the module. Of the measured 0.045 in. profile, 0.015 layers of pottant reside above and below the cell surface with an additional 0.015 in. layer filling the space between the cells. Subtracting the volume of the cells (at a 70% packing factor) from the encapsulant layer, the volume of pottant used was calculated to be 5 cubic inches per square foot of module surface. The cost of the pottant may be found by multiplying this figure by the cost per unit volume of the resin. The cost of the EVA compound was determined by simply adding the costs of the individual components in the formulation times their respective weight fractions. This was calculated to be \$0.7408 per lb. (\$0.0267 per cu. in.) for the clear compound and \$0.6985 per lb. (\$0.0252 per cu. in.) for the pigmented compound.

An estimation of the total encapsulation cost can be calculated by adding in the costs of the other construction elements, as in the following table:

Estimated Module Encapsulation Costs⁽²⁾

| Material | $\$/\text{Ft}^2$ | |
|-----------------------------------|-------------------------|-------------------------|
| | Superstrate | Substrate |
| EVA, clear | 0.0889 | 0.0889 |
| EVA, pigmented | 0.0419 | 0.0419 |
| Primer, SS-4179 ⁽¹⁾ | 0.0066 | 0.0066 |
| Soda-lime Glass (90 mil) | 0.26 | --- |
| Hardboard, Super-dorlux (1/8 in.) | | 0.10 |
| Total Encapsulation | \$0.397/ft ² | \$0.237/ft ² |

(1) Primer applied at a weight of 0.5 gram (0.001 lb.) per ft².

(2) Calculated on the maximum volume price reduction (1979 dollars).

Module Warp

Modules prepared using Super Dorlux substrates all appear to warp during and after the vacuum bag encapsulation step. This is believed to be primarily due to internal moisture changes within the hardboard. An experiment was done to test this hypothesis. A two cell substrate module was exposed to an 80% RH environment for 48 hours. A considerable warp developed along the long edge of the module: approximately 1/4 inch over an 8 inch span. The module was then placed in a vacuum oven at 50°C and evacuated for a period of 3 hours. The warp vanished and the module assumed its desired flat contour. The unencapsulated side of the module was painted (Rustoleum-white) immediately upon removal from the vacuum oven and the paint permitted to dry under ambient temperature and humidity conditions. The warp reformed slowly over a period of two days, but was much less than before, in the order of 3/32 inches over an 8 inch span. This suggests that the paint is retarding the influx of water vapor into the hardboard. An occlusive backside coating of some minimum thickness might be sufficient to achieve a humidity balance in the hardboard and therefore serve as a warp resistant coating. This approach will be investigated in future work.

VI. ADHESION STUDIES

Adhesives, primers or some other mechanism are necessary for the high reliability bonding of the assembly components to one another in order to insure the structural integrity and long life performance of the module. The adhesion between the pottant and other components, i.e., substrate, superstrate and outer cover, was investigated in the past quarter and some encouraging results were obtained with the use of primers. An advantage is presented by the use of ethylene/vinyl acetate copolymers as pottants because these materials have adhesive properties to begin with and are widely used in the industry in the formulation of hot-melt adhesives.

Primers were investigated instead of adhesives in order to generate the highly dependable bonds needed between the components. Primers were selected for initial investigation because of distinct advantages over adhesives they present, which are as follows:

- a. Cost effectiveness, only a very thin layer is required to create an effective bond.
- b. Primers are frequently 100% active systems requiring no drying times to remove solvent vehicle.
- c. High transparency, such a thin layer is used that no loss of transmission is encountered in the optical path.
- d. Adhesion usually occurs by chemical bonding, giving a high dependability bond.
- e. Easily applicable to surfaces by dip or spray process or any technique for low viscosity fluids.
- f. May be incorporated by blending into the pottant before the encapsulation step to give a self priming composition.
- g. Rapid bonding...no lengthy cure cycle required.

Table 4 (page T-5) shows the results of adhesion bond strength evaluations of materials and primers investigated to date. The test specimens were prepared in a manner similar to that which would be encountered in actual module fabrication. All substrate/superstrate specimens were evaluated by ASTM method D-903 for the peel or stripping strength of laminates, in which the polymer layer is pulled back off the substrate at a 180 degree angle. For flexible specimens, such as polymer bonded outer cover materials, ASTM method D-1867 ("T"-Peel) was employed. All values are reported as pounds of stress per inch of width of bond line. Specimens showing high control values were further tested after water immersion for two weeks and exposure to boiling water for periods of two hours and twenty

four hours. According to one researcher, 2 hours of boiling water is approximately equivalent to one year of water exposure outdoor weathering^(a).

In substrate module constructions, pigmented white or possibly clear EVA is to be bonded to Super-Dorlux hardboard. The bond strengths were found to be satisfactory after molding and curing without the use of any primers or adhesion promoters. Molding plain stabilized EVA to the surface of Super-Dorlux gave a good bond that failed by cohesion in the polymer at a break strength of 24 lbs. per inch with no surface treatment. Adhesion of the white pigmented compound under the same conditions did not perform quite as well, producing bond strengths averaging 12.3 lbs. per inch of width.

Sanding the substrate first does not appear to significantly improve the adhesion probably due to a loosening of the immediate surface (A8912-4). Drying the Dorlux before bonding (A8912-7) resulted in greatly reduced adhesion, with an average bond strength of 4 lbs./in. of width. The best adhesion with white EVA was found when the surface was primed with SS-4179 silane (or A8330B silane). This treatment resulted in cohesive failure within the polymer at 24 lbs./in.

The concept of incorporating the primers directly into the resin was investigated in order to assess the feasibility of eliminating the priming step entirely. This would eliminate a production operation and, therefore, speed up the large scale module fabrication process.

Primers combined internally with the polymer were not quite as effective in promoting bond strength. One part per hundred resin of mixed silane (A-8121-2) in the polymer formulation gave an acceptable strength of 17.1 lbs./in. When these two components are forcibly separated, the failure occurs principally within the immediate surface of the hardboard and EVA pulls away with a thin covering of Dorlux attached to it. Soaking in hot (60°C) toluene for several hours followed by forced separation leaves a layer of strongly adhering EVA on the surface of the hardboard that appears to be chemically bonded.

Surface delamination within the hardboard appears to be the biggest potential problem with this material and indicates that the bond strength will be limited to the cohesive strength of the surface. Some sort of surface hardening treatment may be possible if higher bond strengths are found to be desirable.

(a) Edwin P. Plueddemann, Dow Corning Corporation, private communication.

Water immersion of the hardboard specimens was found to be an inappropriate test method in most cases. Only two specimens, white EVA to sanded Dorlux and EVA with internally compounded primer (specimen A8930A), retained good bond strengths of 12 to 14 lbs/inch. All specimens that failed (by peeling) revealed the failure to be in the immediate surface of the hardboard and the polymer pulled away with a covering of wood fibers on the surface. Boiling water immersion reduced all the bond strengths to an average value of 2 lbs/inch. These experiments indicate that isolation from liquid water is essential for long bond life with hardboard products.

Adhesion to glass does not occur as readily as to hardboard and the use of primers is absolutely necessary to obtain any peel strength at all. The EVA formulation molded and cured directly over the glass has essentially no adhesion (0.3 lbs./in.). The approach to bonding glass was essentially the same as for hardboard, using primers both within the polymer and applied to the surface, the sides were differentiated, however. Soda-lime glass is prepared by a process of floating the melt on a bath of molten tin. This results in the glass having two sides, an air side and a tin side, which may give very different adhesive characteristics. The sides were identified with the use of an ultraviolet light (shortwave - 256 nm) which causes the tin side to fluoresce with a pale yellow glow. The air sides were labeled A or 1 depending on which lot of glass was being tested.

Excellent results were obtained with both techniques. For surface applied primer, the most effective treatment was found with A8330-B (Table 5). In use, this primer is swabbed onto the surface of glass that has been precleaned with detergent, acetone and rinsed in distilled water. The coating weight (wet) is approximately 0.5 grams or .001 lbs. per square foot. After an air dry period of half an hour at ambient temperature the glass is ready for lamination.

A8330B gave a control value of 21.9 lbs./in. and did not appear to be affected by immersion in either room temperature or boiling water. Two weeks water immersion at room temperature gave a bond strength of 23.5 lbs./in. (average) and 24 hours in boiling water only reduced the bond to 17.5 lbs./in. In all the specimens the bond was broken by cohesive failure in the polymer, marked by a (b) next to the break strength in Table 4.

Internally blended primers (one part per hundred resin) also gave good results, the best overall A8921-2 primer. Control values were found to average 23 lbs./in. and immersion in boiling water for 24 hours gave a fifty percent reduction to 11 lbs./in. All specimens also failed by cohesion in the polymer. Only in one case did a significant difference appear between the air side and the tin side; internally blended SS-4179 gave significantly higher bond strengths on the tin side.

Of the formulations and techniques tried with glass, the best on an overall performance basis are surface applied A8330-B and internally blended A8921-2. Both these formulations are equally effective on both sides, and give control bond strengths of 20-30 lbs./in. After 24 hours in boiling water the bond is still intact at 17.5 lbs./in. (A8330B). These two formulations are also free of the wide variation in values found for many other primers tested^(a).

A few experiments were tried in bonding the EVA pottant to copper and aluminum foil (a potential back over material) but without success. With or without primers no bond strengths of any value were recorded in our study. A different primer system consisting of nine parts of Dow Corning Z-6030 and one part of Z-6020 silanes has been successful, however. Cohesive bond failure after 4 days of water immersion was found for both copper and aluminum^(b).

Bonding the resin to outer cover materials produced variable results. The bond strength to Korad 201-R film gave variable values ranging from 1 to 17 lbs./in. for the water immersion conditions and a less variable and rather low 2.3 lbs./in. control value. Tedlar UT gave a control strength of 13.2 lbs./in. and had less variation in the water immersion specimens. No primers or any other treatment was used with these two films, the bond strengths resulting from free radical crosslinking during the cure of the EVA. The cause of the variation in bond efficiency is not known, however, it is suspected to be a result of surface condition. Perhaps a standardized cleansing procedure of some variety or an appropriate primer will be found that generates predictable results.

(a) Primer formulations are shown on Table 5.

(b) Plueddeman, E., "Chemical Bonding Technology for Terrestrial Solar Cell Modules" JPL Document 5101-132, Jet Propulsion Laboratory, Pasadena, California, September 1, 1979

VII. OUTDOOR AGING

At the beginning of this contract effort (May 1977), twenty four polymeric materials were selected for study on the basis of their transparency and weatherability. Although most of these originally investigated polymers were found to be cost ineffective and/or not amenable to any processing method that could be used to encapsulate solar cells, a study of their properties provided valuable experience towards the selection of more successful candidates, such as EVA. The initial choice of materials was directed solely at transparent pottants and did not include other possible construction elements such as substrates, however, some of the polymers could possibly serve as protective outer covers in later phases of this program.

As a continuation of this original program, data was obtained from outdoor exposures as well as from the initial accelerated aging exposures so that correlations between natural and artificial accelerated environments might be made. From these original twenty four plastics a group of eleven were chosen for outdoor weathering studies. Tensile bar samples were put outdoors in Florida and Arizona at 45° angle exposure, and in Arizona in the EMMAQUA (a device combining natural sunlight with artificial acceleration by means of mirror concentrators plus a water spray). Specimens were withdrawn at various time intervals and evaluated for optical transmission and mechanical properties.

Two materials required special preparation: PVB and Q3-6527 gel. In the case of the polyvinyl butyral (PVB - "Saflex" PT-10), it was desired to expose the material behind glass in order to simulate use conditions. Bonding to the glass occurred, however, and necessitated that the material be sandwiched between 1-mil films of FEP first to serve as release surfaces. Q3-6527 dielectric silicone gel was also exposed behind glass by pouring the uncured liquid into a glass cell (3-1/2" x 1" x 0.062") and permitting polymerization to take place. Only a visual inspection could be used to evaluate these last two materials, as the specimen would not fit into a spectrometer or Instron tester.

In addition to tensile specimens. 34 miniature two-celled, electrically active modules were constructed from the most promising materials considered at that time. Six different constructions or "systems" were built using the materials in the following tabulation:

Two-Celled Modules

| <u>System Number</u> | <u>Substrate</u> | <u>Pottant</u> | <u>Cover</u> |
|----------------------|--------------------------|----------------|-------------------|
| 5 | Filled polyester | RTV-615 | Halar 500 |
| 6 | Filled polyester | Sylgard 184 | PFA 9705 |
| 7 | Filled polyester | Viton AEV | Plexiglas DR-61-K |
| 8 | Filled polyester | Q3-6527 | Plexiglas V-811 |
| 12 | Aluminum | Q3-6527 | Soda-lime glass |
| 13 | Glass/epoxy Nema C-10 | Sylgard 184 | Tedlar 400SG 20TR |

These modules were fabricated using appropriate primers, adhesive, and cure cycles to give optimum life (see Springborn Laboratories Annual Report dated July 1977 - "Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants"). Mechanical stability was judged from visual inspection, and electrical performance was determined by measuring the short-circuit current (I_{sc}) before and after exposure.

All mechanical test specimens and experimental minimodules have completed their exposure times under various conditions. Table 6 outlines the performance of the two-celled modules after four and eight months of exposure to EMMAQUA, Weather-Ometer, and RS-4 sunlamp. Probably the best performance was found for the system (No. 5) using the RTV-615 pottant with a Halar 500 fluorocarbon cover. Apart from slight discoloration of the substrate, the modules appeared to have experienced no damage. Other systems varied from complete deterioration (Viton AEV pottant; Plexiglas DR cover) to minor damage (Sylgard 184; EPA cover).

The eight modules using Q3-6527 dielectric gel performed well but formed bubbles in all cases. This may be a result of shrinkage caused by further polymerization occurring at a slow rate during the exposure time.

The Sylgard 184/Tedlar 400SG 20TR cover system failed badly, the Tedlar delaminating, cracking, and becoming brittle - especially after RS-4 exposure (see Figure 10).

The short-circuit currents (I_{sc}) retained high values in most cases, averaging 90-100 percent of original measurement. Four modules tested had currents in excess of control values, perhaps due to an increase in optical coupling between the encapsulant layers. The lowest value found was 32.5 percent for the badly degraded Sylgard 184/Tedlar 400SG 20TR module.

Mechanical test specimens of ten polymers selected for study were evaluated after exposure to the following conditions:

| <u>Condition</u> | <u>Months</u> |
|---------------------------------|---------------|
| Phoenix, 45° south, fixed angle | 12 |
| EMMAQUA | 12 |
| Florida, 45° south, fixed angle | 12 |

The test results are contained in Table 7 through 9. The properties measured included ultraviolet and visible transmissions; and yield strength, modulus, ultimate elongation, and tensile strength. As expected, the fluocarbons showed the greatest resistance to weathering. Tedlar performed very well under these conditions, decaying to 80 percent of its tensile strength after 12 months of EMMAQUA exposure. All other materials were affected to some degree, 12 months of EMMAQUA being the worst condition.

Plexiglas DR, a grafted rubber formulation, appeared to outperform Plexiglas V-811 (homopolymer), retaining higher percentages of tensile strength and elongation. Sylgard 184 did well in all previous cases; unfortunately, the 12-month EMMAQUA specimens were missing, having torn away from the mounting board during exposure.

The most consistent loss of properties was noticed for PVB. Every test specimen in every condition flowed to an unrecognizable mass that could not be tested (see Figure 11). The light yellow color of the melted polymer suggests that degradation has also occurred. Experiments conducted by the manufacturer (Monsanto) are in agreement with our results, and they indicate that an oxygen/UV synergism occurs that degrades this compound rapidly. The exclusion of air is the reason why PVB becomes stable and functions successfully as a safety glass interlayer. Monsanto's statement that this product (Saflex PT-10) is not intended for outdoor use in nonlaminated constructions is in agreement with our experimental findings.

Tables 10 through 12 compare the percentages of tensile strength, elongation, and optical transmissions retained by these materials in various exposure conditions. The best overall retention of mechanical properties is found for the fluorocarbon polymers - especially FEP. Halar, Kel-F, and Tedlar are not quite as stable. Plexiglas acrylic formulations also demonstrate good performance, particularly Type DR, retaining 60 to 100 percent of original tensile strength. Tenite 479-CAB, and Lexan polycarbonate lost almost all elongation and degraded severely under all exposures.

The best optical transmissions retained, in terms of net transmission, were found for the Plexiglas acrylics and Kel-F fluorocarbon.

This study demonstrates that silicone, acrylics and fluorocarbons have the best weathering properties, as is generally acknowledged. Corrosion effects on the metal interconnects were more noticeable with silicone potting, however, probably due to the high water vapor permeability. The rapid degradation of polyvinylbutyral (PVB) in the presence of oxygen indicates that this material will have to be isolated from the atmosphere if it is to survive as a solar cell encapsulant. Tedlar, a candidate outer cover film, dropped to about 30% optical transmission in all weathering conditions and physically deteriorated in a number of cases. Although Tedlar has been reported to weather acceptably, this particular grade, 400SG 20TR, did not give encouraging results.

Even though the deterioration of some of the test modules was quite apparent (e.g., delamination, water spotting, discoloration, etc.) very little effect on short circuit current, I_{sc} , was noticed. The modules degraded more in terms of their construction and appearance than in their power input.

VIII. OUTER COVERS FOR SUBSTRATE DESIGN MODULES

Soft elastomeric materials must be used for pottants in order to prevent cracking of the silicon cells due to stresses resulting from thermal expansion differences. Soft materials are prone to soiling and dust retention, however, which reduces the light transmission and impairs the module efficiency. Hard coatings are, therefore, desirable to avoid this problem. Additionally, the function of UV screening is required for the outer cover in order to reduce the effects of photolytic degradation and provide the maximum useful lifetime for the pottant and other components.

The properties of an idealized outer cover may be stated as follows:

- (1) High optical transparency.
- (2) Compatible refractive index properties to the pottant that favor optical coupling.
- (3) Chemical compatibility with either the pottant or a suitable primer or adhesive to insure a high reliability bond that will not delaminate during the useful lifetime of the module.
- (4) Inherent weatherability.
- (5) Ultraviolet light screening properties to protect the underlying pottant.
- (6) Anti-reflective properties to increase the total light transmission (if used on the sunlit side).
- (7) Resistance to thermal cycling without melting, cracking, or deforming.
- (8) Surface hardness sufficient to retard soiling and to withstand cleaning processes in routine maintenance.
- (9) Abrasion resistance to prevent loss of material or sufficient haze to impair the transmission characteristics.

a. Coatings

In previous work, experiments were conducted to determine the feasibility of preparing tough low-cost, UV-absorbant coatings. Solution acrylic coatings were chosen as the vehicle (Acryloid series; Rohm & Haas Company) due to their low cost, transparency, and inherently excellent weathering characteristics. UV

absorbers were blended into the coating formulation and subsequently cast and dried into films 0.001 inch thick.

Transmittance measurements show these films to be approximately 80 percent transmissive in the visible regions, and from zero to 11 percent transmissive in the ultraviolet range. Four formulations had no transmittance at all in the UV region, and these ranged from \$0.0092 to \$0.0122 per square foot per mil in cost.

To test the efficacy of these coatings, an ultraviolet degradable polymer, polypropylene (Profax 6523, Hercules Chemical Company), was coated to a 1-mil thickness and exposed under the RS-4 fluorescent sunlamp. An acrylic coating formulation containing 5 phr Tinuvin P and 1 phr Cyasorb UV-1084 was the most promising, demonstrating approximately a fifteenfold increase in the useful life of polypropylene.

All these film formulations had difficulties associated with their use, however, the optical transmission was not as high as would be desirable, the dried films were brittle and hard to handle and the UV absorbers were capable of leaching out of the film, leaving it without its protective function.

More recent investigations of solvent based coatings have involved work with some custom made acrylic copolymers prepared by National Starch and Chemical Corporation. These solvent/polymer compositions are similar to the Rohm and Haas acrylic coating Acryloid B-44, except that the composition has been modified with a UV absorber during the polymerization stage. The UV absorber is a product of National Starch and Chemical and is referred to as Permasorb-MA. This compound is a benzophenone type UV absorber that has been appropriately chemically modified with a vinyl functional group, permitting it to be homopolymerized or copolymerized to a high molecular weight with other monomers. Three formulations were evaluated for effectiveness as UV screening films, each varying in the amount of UV absorber present:

| <u>Number</u> | <u>Solids, %</u> | <u>Copolymer, % Permasorb-MA</u> |
|---------------|------------------|----------------------------------|
| 38B | 39.2 | 2.5 |
| 42A | 41.4 | 5.0 |
| 42B | 40.6 | 10.0 |

Clear flexible films were easily cast, and showed UV screening properties similar to formulations where the monomer was just mixed in rather than copolymerized. The cut-on frequency was fairly sharp, beginning at about 365 nm, with

no transmission peaks in the lower ultraviolet (No. -42A; 3-mil film). Permasorb-MA appears to be approximately equal to Cyasorb UV-531 (American Cyanamid) in absorption efficiency but has the advantage of being nonextractable in polymer systems where it is used as a comonomer. The protective efficiency of these coatings is being compared, as before, by means of coating specimens of polypropylene and examining the rate of degradation during fluorescent sunlamp exposure.

To date, 2-mil films over polypropylene appear to have provided excellent protection during a 54 week exposure period. No evidence of chalking, cracking, or discoloration can be noticed, and the test specimens retain their original flexibility. Unprotected, polypropylene crumbles after about 150 hours of exposure. This is equivalent to a sixty-fold increase in performance.

b. Films

Although the solvent based coatings have demonstrated the ability to provide adequate protection to polymers exposed to UV radiation, they are inconvenient to use. Whatever the method of application, a problem with solvent removal exists. When applied directly to the surface of the module, marring also occurs from solvent attack of the underlying pottant. Preparing dried films first necessitated long drying times and film handling equipment. An adhesive would also be required to bond the film to the module surface in an additional coating step. Due to these difficulties surveys were conducted into the existence of commercially available films that could possibly serve these functions.

The first requirement is that the film be highly transparent in order to insure maximum power output from the underlying cells. An optical transmission of 90% or better is desirable. The second requirement is that the film be inherently weatherable due to its placement on the outer surface of the module that will receive the greatest exposure to the elements. Only three classes of polymeric materials have been identified as being inherently weather resistant, silicones, fluorocarbons and acrylics. From these classes, only fluorocarbon and acrylic polymers have been identified as being produced commercially in transparent film form. Only one fluorocarbon film has been identified as a possible candidate for use as an outer cover to date; Tedlar film (DuPont). In addition to having high optical transparency (91% - total integrated) this material is available with an ultraviolet absorber already compounded. The particular grade selected for investigation is 100BG30UT. The properties of this material are as follows:

| | |
|------------------------------|-------------|
| Tensile Strength (psi) | 18,000 |
| Yield Strength (psi) | 6,000 |
| Elongation, % | 115 |
| Tensile Modulus (psi) | 250-300,000 |
| Dielectric Strength Kv/mil | 3.4 |
| Refractive Index, n_D | 1.46 |
| Optical transmission (1 mil) | 91% |
| Cost $\$/ft^2/mil$ | 0.0482 |
| $\$/m^2/25\text{ nm}$ | 0.518 |

The film is available in roll form with four different grades of gloss, and has the option of being treated to yield one side adherable for use with adhesives, coatings and laminations (100 BG30 UT). Tedlar is an extremely tough polymer with excellent resistance to both thermal and mechanical stress and also combines hardness and a low surface tension for ready cleanability. Questions remain about the weatherability of Tedlar, however. Springborn Laboratories has exposed tensile specimens and module prepared with Tedlar to direct sunlight in the EMMAQUA accelerator at DSET, Inc. in the Arizona desert and recorded destructive degradation. DuPont has recently introduced a "solar energy" grade intended for thermal collectors, referred to as 400XRB160SE. After five years of Florida exposure they report a 95% retention of transmission characteristics and about a 50% retention of physical properties (DuPont Bulletin TD-31). Although the initial properties are high the degradation rate still suggests that this material will not perform satisfactorily for a period of twenty years outdoors. Additionally, the cost is high at almost \$0.05 per square foot in the thinnest grade available (1 mil-25 μm). As Tedlar is the least expensive of the fluorine-containing films, generally, it may be assumed that the fluorocarbons are too expensive for use in this application.

A product from the acrylic family has recently been introduced to the market. This is an extruded film product with high transparency and a UV absorber already compounded into the resin. The cost has not been fixed yet, but is anticipated to be in the order of \$0.016 per square foot per mil or approximately \$0.17 per square meter per 25 μm of thickness. This product line is tradenamed "Korad".

The outer cover of current use and interest is Korad X201-R, supplied by Xcel Corporation, Newark, New Jersey. This product is an acrylic film, available only in a 3.0-mil thickness and not yet commercial; however, commercial development is currently under way. This copolymer film has the following properties:

| | |
|------------------------------------|------|
| Tensile strength, psi | 4400 |
| Yield strength, psi | 4200 |
| Elongation, % | 130 |
| Light transmission, % | 92 |
| Haze, % | 1.3 |
| Gloss at 60° | 92 |
| Glass transition (T _g) | 88°C |

In the recent module fabrication experiments, 201-R was incorporated into the encapsulation package prior to vacuum-bag fusion and cure. The film was placed as a cover over the top piece of EVA in the substrate construction, based on Super-Dorlux. After vacuum-bag lamination the film was found to be physically unaffected, formed a smooth transparent coating over the EVA, and was strongly bonded to the surface. A miniature module was immersed in water for a one-week period. No evidence of delamination of the Korad film could be noticed.

No primers or adhesives were used with the film in the lamination process. The bonding is thought to be a result of the cure mechanism of the EVA. Free radicals generated by the decomposition of the peroxide cause the crosslinking of the EVA by abstracting a hydrogen atom from the polymer chain and then permitting the polymer macroradicals to recombine, thereby forming the crosslink. This is also a known effect in polymers of acrylates, which are probably a component of the Korad film.

It is suspected that the film is chemically crosslinked to the EVA surface in the fusion/cure process and requires no further adhesive aid. Critical and quantitative studies of adhesion and permanence will follow. The cost of the 201-R film is expected to be in the order of \$0.05 per square foot.

An additional possibility for this film is that of chemical modification of the surfaces. Saponification of the surface with dilute alkali may be used to regenerate carboxylic acid functionalities which could then be ion exchanged with an ion such as aluminum. There may then result surfaces with improved properties such as increased abrasion resistance, rain and humidity resistance, and more closely matched refractive index characteristics.

A disadvantage to the use of Korad 201-R film is the fugitive nature of the UV absorber that is necessary to provide the protective property of the film. Xcell Corporation has stated that the UV absorber (Dioctyl benzophenone) is lost after about two years of outdoor exposure, thereby leaving the film transparent to the shorter wavelengths. This would result in the degradation of the underlying pottant. Experiments are currently underway to determine a method of chemically reacting a UV absorber into the Korad polymer prior to the film extrusion process, thereby binding it permanently.

Under a separate JPL contract (No. 954995) Dow Corning Corporation, Midland, Michigan, has synthesized experimental quantities of a silicone/acrylic coating material that contains chemically incorporated Permasorb-MA. In addition to its high transmission and UV screening permanence, this film has the properties of water resistance, oil resistance and surface hardness. These properties have been found to be desirable in providing a soil resistant and easily cleanable surface. This promising new coating will be thoroughly evaluated for field performance by Springborn Laboratories in future phases of this program.

IX. CORROSION STUDIES

Experiments were conducted to determine the relative amount of corrosion protection that could be provided to the cells and other metallic components by encapsulation in EVA. This experiment used the ASTM procedure number B-117 in which coated specimens are exposed to a salt fog containing 5 parts by weight of sodium chloride and at a temperature of 35°C. This test is generally regarded as severe and causes rapid corrosion of inadequately protected metals.

Materials included in this test were aluminum, mild steel, galvanized steel, copper and whole solar cells both primed and unprimed. Specimens were prepared by compression molding discs between two sheets of EVA and curing as usual. This gave a fairly uniform coating of approximately 10 mils (0.25 mm) thickness. A second set of specimens was prepared with cut edges to reveal the depth that the corrosion would penetrate from an exposed edge. In addition to these specimens, some experimental corrosion monitors were prepared. These units consisted of a copper mesh/zinc mesh galvanic couple separated by a layer of EVA and then totally encapsulated in EVA. The purpose of these units was to record any galvanic action that might occur in the event that transmission of water vapor and ions took place in the pottant.

The results of salt fog exposure after varying lengths of time are recorded in Table 13. The unencapsulated control specimens developed signs of corrosive attack within the first few days, the most sensitive being copper and the mild and galvanized steels which formed oxidation products within the first six hours of exposure. Aluminum began to show signs of attack after about 3 days. The mild and galvanized steel specimens with the edges exposed were also the first to show signs of attack after about 3 days. The mild and galvanized steel specimens with the edges exposed were also the first to show signs of attack but with no significant delamination occurring for about 300 hours exposure. At this point, the aluminum and copper exposed edge specimens began to show signs of corrosion, and the pottant covering receded by about a millimeter. All the fully encapsulated specimens performed remarkably well. The first to show attack was, again, the mild steel which showed surface dulling and some color formation after 450 hours exposure. In contrast, the aluminum and copper specimens were still unaffected after 1600 hours (10 weeks) of salt spray and retained their original bright surfaces. The encapsulated

solar cell performed similarly well and gave no appearance of attack. The use of primers did not appear to be influential in inhibiting the rate of corrosion or the delamination that eventually occurred on the specimens where one edge was left exposed.

The galvanic corrosion monitors were tested with a sensitive voltmeter at each time interval and no current was observed, even after visible signs of corrosion (color formation) appeared. This serves as an indication that no ionic species are present in the polymer that result in a conduction path.

After the initial 1600 hour exposure period, the test was continued but in a modified form. Exposure alternated on a weekly basis between continued salt spray and RS-4 fluorescent sunlamp exposure, the intention being to observe any synergistic degradation that could result from the combined stresses. After four additional months, amounting to a total of 1800 hours of salt spray and 200 hours of RS-4 radiation, the test was discontinued. The EVA began to show signs of degradation, surface cracks appearing on many of the specimens and occasionally a hole opening in the encapsulant layer. The degradation effects appear to be worse in areas where drainage of the salt solution was impeded and tended to accumulate. At this point the completely encapsulated specimens of aluminum, galvanized steel, copper and solar cells all appeared to be in good shape with no signs of corrosive attack. It may be concluded that thorough encapsulation with EVA provides excellent protection to most of the sensitive metals studied. Although plain mild steel is not as easily protected, its galvanized counterpart appears to perform very well in providing long term performance when encapsulated in EVA.

X. SEPARATOR MATERIALS

Materials are being investigated to provide mechanical barriers between module components that require a positive separation between each other for proper functioning. Two classes of separators have been identified to date, non-woven cloths and "scrim" materials. The non-woven cloths consist of a mat of randomly oriented fibers held in position with a small quantity of binder.

A scrim is defined as a cloth of very open weave such that holes or "cells" of a specific size are present throughout the body of the weave. The reasons for the use of these materials are as follows:

- a. The scrim would provide for a fixed distance between the cell and substrate, insuring a complete encapsulation in the pottant, and providing stress relief.
- b. The scrim material placed behind the cells in the superstrate design would serve to maintain the insulation resistance between cell and back cover (especially if the cover is aluminum foil).
- c. The scrim serves to prevent the overlap of pigmented white EVA over the cell surface during the melt stage in vacuum bag fabrication. This eliminates the necessity of using an additional piece of clear EVA behind the cell.
- d. The scrim provides air channels between the polymer layers that aid in evacuation during the vacuum bag process.
- e. The scrim/separator would provide electrical isolation between the cells and substrate in modules using sheet metal substrates such as galvanized steel.

A list of potentially useful low cost scrims appears in Table 14. Selected scrims of several geometries and compositions were evaluated by fabrication into one cell modules. Four scrims and one glass cloth were used:

- a. Baytex, QX 8410/F-14, 10 mil, polyester
- b. Apex Mills, Duralon S-50, 8 mil, nylon
- c. Apex Mills, Alto, 5 mil, nylon
- d. Windsow screen, 12 mil polyester
- e. General purpose glass cloth, 8 mil, glass (woven)

All products were useful in helping to retard the flow of pigmented EVA to some degree, the best being the glass cloth due to its small hole size. Air entrapment in the cells of the weave was a problem in some of the modules, those using monofilament weaves.

It is strongly suspected that multiple air channels along the fiber of the scrim or cloth are required for proper evacuation of the module during the fusion process. Large weaves of single filament materials invariably trapped air in the cells and particularly in the center of the module. Glass cloth is superior in this respect, presenting the least difficulty with air entrapment and the most efficient evacuation. Glass cloth is also sufficiently white and reflective that it may be possible to eliminate the pigmented EVA if the replacement is determined to be cost effective.

The scrim addition is expected to result in a module cost-add on in the order of \$0.015 to \$0.025 per square foot.

Due to the improved properties of glass cloth, experiments continued to determine its usefulness. A wide variety of woven glass products are available, the largest supplier being Burlington Glass Fabric Company, Rockleigh, New Jersey. The cost is expected to be in the range of .04 to .06/ft².

In summary, the scrims examined were difficult to use for a number of reasons: the fabric was dimensionally unstable, the weave distorting easily when laid down on the module; the white pigmented EVA was not held in place as effectively as expected, some pigment overlapping onto the cells; the edges presented a problem because the cloth hung out and did not bond tightly.

Many of these problems were solved with a totally different concept; that of fibrous non-woven textiles. Two kinds appear to be available; glass and polyester. The polyester textile is used primarily for electrical insulation and is available from Pellon Corporation, Lowell Mass. The least expensive textile they produce costs about \$0.019/ft² at a thickness of 1.2 mils. The non-woven glass textiles are more desirable in that they are less expensive for greater thickness and are more inert. They are made by Crane and Company, Dalton, Mass., and distributed through Electrolock, Inc., Chagrin Falls, Ohio. The major advantage that the glass products have over the polyester materials is cost. The least expensive polyester (see Table 15) is 1.9¢ per ft² for a 1.2 mil thick textile. This is equivalent in cost to a 12 mil thick glass cloth from Crane & Co. The best grade of non-woven glass cloth found to date is "Craneglass 230" which is manufactured primarily for electrical insulation and uses a less expensive and larger diameter fiber. Some of the useful properties stated by the manufacturer are:

Design Flexibility - Available in thicknesses of 3, 5, 7, 9, 12, 15, 20, 30, 60 and 125 mils.

Thermal Endurance - Craneglas 230 is unaffected by high temperatures. The resin or laminating material alone determines the temperature limits of the system.

Positive Space Factor - Craneglas 230 won't degrade under high temperature and shock. It remains intact as a positive spacer under abnormal temperature and load situations.

- . Dimensional Stability - The glass fibers won't stretch, shrink, swell or warp.
- . Fracture Resistance - Some saturated reinforcing webs will fracture when folded or creased. Craneglas 230 resists this problem because of random orientation and natural softness of the low denier fiber.

Improved Dielectric Performance - Even wetting-out of resin. Resin rich areas a source of potential dielectric failure in woven structures, are eliminated.

Improved Workability - Craneglas 230 is easy to handle in its natural web form. In saturated or laminated form, it can be easily machined.

Increased Economy - Significant cost-performance improvement is realized from Craneglas 230 because of its lower first cost.

The materials of interest for module construction would be the 3, 5 and 7 mil weaves, costing 0.66, 0.78 and 0.97 cents per square foot, respectively (see Table 16). These are the least expensive cloth materials found to date. Two cell modules have been prepared in the laboratory using these scrim materials with encouraging results. The non-woven cloth serves to separate the cell from the substrate without the danger of an interconnect or solder high point coming through a hole as could be the case with the open cell materials originally investigated. Migration of the pigmented layer is also no longer a problem, the pigment appears to be totally restrained by the cloth.

Modules have been successfully prepared using the scrim cloth and eliminating a layer of clear EVA; as follows: substrate, white EVA, scrim, cells, clear EVA, top cover. This eliminates a layer of potting which results in another cost saving step for module fabrication.

Currently, the cost of pigmented EVA, in the thickness used, is approximately \$0.042 per square foot.

The use of glass cloth replacement of an EVA layer results in approximately a 13% saving of the allotted \$0.25 for the encapsulation goal.

XI. SUBSTRATE ANALYSIS

The results of surveys to find suitable candidates for the various construction elements indicate that the load bearing substrate (or superstrate) will be the most expensive component in the encapsulation package. Based on the 1980 encapsulation cost goal of \$3.78/m², the substrates will have an estimated allocation of about \$2.10/m², or 56% of the total. Alternatively, the system cost may be expanded to \$14.00/m² (1980 dollars) if the support frame and mounting is included.

In previous work only flat sheet materials were considered, however, ignoring structural designs that could possibly result in lighter weight, lower cost, and more efficient use of materials. The following is an abbreviated engineering analysis of grid and sandwich panel substrates, including a component cost analysis and projected total encapsulation cost based on current construction element prices. The approach used has been to calculate the required dimensions of possible conformations and combinations of construction materials such that they form panels meeting the specification (JPL) for deflection under uniform wind loading. The quantity of materials used and their prices permitted comparative costing of the trial designs. All pricing is in 1978 dollars.

Wind Loading

Wind is essentially the only load to which the panel will be exposed. Under current solar module performance guidelines, the panels must be able to withstand uniform wind loadings of 2.4kPa (50 pounds per square foot) without flexing to the point at which some form of failure occurs. Assuming that the other components make no structural contribution, the substrate will carry the entire load.

Considering a substrate panel of length L and width W subjected to wind loading at a velocity V and density σ . The resultant unit wind load (drag) D would be:

$$D = C_D \sigma \frac{V^2}{2g}; \text{ where } C_d = \text{drag coefficient}$$

g = gravity constant

In the worst case, the panel would be positioned normal to the wind direction. For the particular case of 15" x 45" (0.4 x 1.1 m) substrates, the aspect ratio in the wind direction would be 45/15=3. From aerodynamic charts, the resulting drag coefficient C_D would be approximately 1.30. In consideration of the design wind velocity of 120 mph (176 ft/sec), the air density σ would be approximately 0.078 lb/ft³. At these conditions the unit wind load would be:

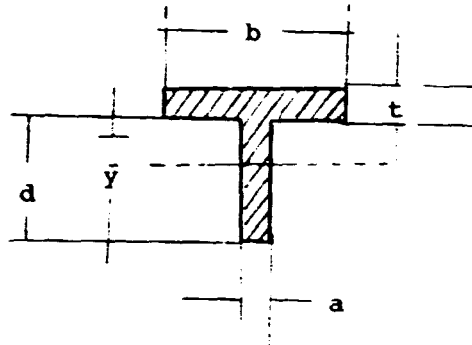
$$D = 1.30 (0.078 \text{ lb/ft}^3) \frac{(176 \text{ ft/sec})^2}{2(32.2 \text{ ft/sec}^2)}$$

$$D = 48.8 \text{ lb/ft}^2 \text{ (minimum)}$$

$$\text{Let wind load } D = 50 \text{ lb/ft}^2 \text{ (0.347 psi)}$$

Analysis of Grid Panels

Consider a ribbed grid panel of one material of a simplified geometry as shown,



where b is the rib spacing and the width of the strip beam, t , is the flange thickness, d is the rib depth, a is the web thickness, and \bar{y} is the distance to the neutral axis as indicated. The strip beam would span the 15 inch direction and the panel would be supported as in the sandwich panel analysis above. Longitudinal ribs of $d/2$ depth and $2b$ spacing would also be used for self-supporting rigidity.

From the strip beam geometry,

$$\bar{y} = \frac{\sum_{i=0}^n A_i \bar{y}_i}{\sum_{i=0}^n A_i}$$

$$= \frac{bt(2d+t/2) + ad(d/2)}{bt+ad}$$

$$\bar{y} = \frac{ad^2 + 2btd + bt^2}{2(bt + ad)}$$

and

$$I_{xx} = \sum_{i=0}^n (I_{o_i} + A_i \bar{y}_i^2)$$

$$I_{xx} = \frac{bt^3 + ad^3}{12} + bt(d + t/2 - \bar{y})^2 + ad(d/2 - \bar{y})^2$$

The maximum bending stress σ will be:

$$\sigma = \frac{M\bar{y}}{I_{xx}}, \text{ where } M = \frac{Dbw^2}{8}$$

$$\sigma = \frac{Dbw^2\bar{y}}{8I_{xx}}$$

For the required deflection δ ,

$$I_{xx} \geq \frac{5Dbw^4}{384E}$$

Trial grid panel design: assume a grid panel molded of talc-filled polypropylene. Let

$$E = 2.5 \times 10^5 \text{ psi at } 160^\circ\text{F}$$

$$b = 1.50 \text{ in. rib spacing}$$

$$t = 0.0625 \text{ (1/16) in.}$$

$$a = 0.0625 \text{ (1/16) in.}$$

$$\delta = 0.25 \text{ in.}$$

$$D = 0.347 \text{ psi}$$

$$L = 45 \text{ in.}$$

$$W = 15 \text{ in.}$$

$$d = 0.675 \text{ in., rib depth}$$

$$\bar{y} = 0.59181 \text{ in.}$$

$$I_{xx} = 5.590 \times 10^{-3} \text{ in}^4 - \text{satisfactory}$$

Evaluating stresses,

$$\sigma = 1550 \text{ psi} - \text{safe for material at } 160^\circ\text{F}$$

Approximate cost factors for 45" x 45" panel:

| | |
|-----------------|-------------------------|
| Surface volume | 42.1875 in ³ |
| Ribs volume | 19.6172 |
| Stringer volume | <u>5.0413</u> |
| | 66.846 in ³ |

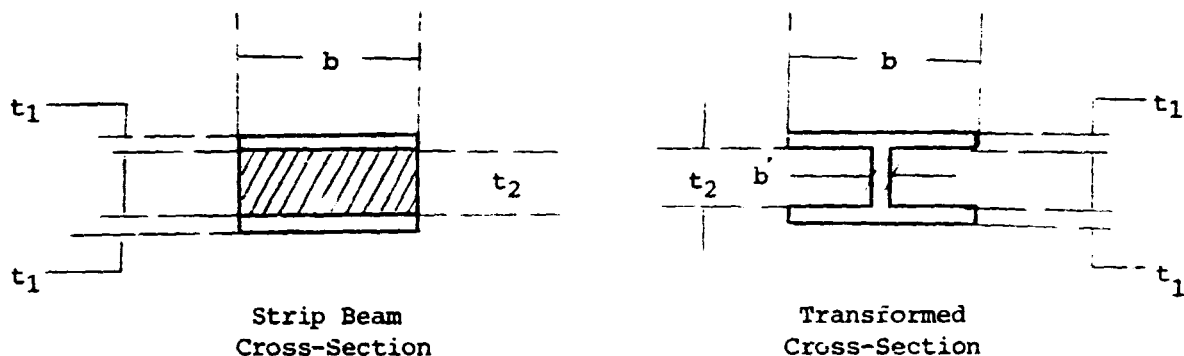
$$66.846 \text{ in}^3 = 2.897 \text{ lb at } 33\text{¢/lb} = \$0.96$$

$$\text{Cost/ft}^2 = \$0.204$$

$$\text{Cost/M}^2 = \$2.20$$

Analysis of Sandwich Panels

Consider a sandwich panel composed of two outer skins, having a flexural modulus of elasticity E_1 and thickness t_1 , bonded or otherwise structurally connected to a core (foam, honeycomb, etc.), having a flexural modulus of elasticity E_2 and thickness t_2 . The structure will be analyzed using a unit strip from the short side (15 inch direction) of the panel, considering that the panel is simply supported along the long sides (45 inch direction). The strip can then be analyzed as a composite transformed to a material of modulus E_1 . The geometry would be as follows:



In the transformed beam,

$$b' = \frac{E_2}{E_1} b, \text{ but } E_1 \gg E_2 \text{ (at least by } 10^3)$$

$$\therefore b' \doteq 0$$

$$\therefore I_{xx} \doteq \sum_{i=0}^n (I_{o_i} + A_i \bar{y}_i^2)$$

$$\doteq 2(bt_1^3/12) + 2bt_1(t_1 + t_2/2)^2$$

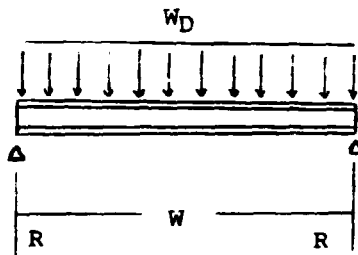
$$I_{xx} \doteq bt_1/6 [4t_1^2 + 6t_1t_2 + 3t_2^2]$$

The beam loading would be as shown, where

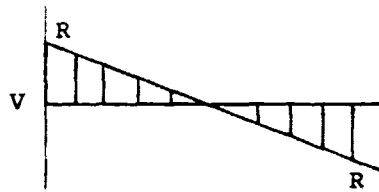
$$W_D = bD$$

$$R = \frac{W_D W}{2} \text{ (and is the maximum shear)}$$

$$M = \frac{W_D W^2}{8}$$



Load Diagram



Shear Diagram



Moment Diagram

Minimum deflection of the center of the span, and the resulting radius of curvature, are the governing factors. The deflection δ is given as:

$$\delta = \frac{5W_D W^4}{384 E_1 I_{xx}}$$

or I_{xx} can be estimated as

$$I'_{xx} = \frac{5W_D W^4}{384 E_1 \delta} .$$

The radius of curvature r_s is given by

$$r_s = \frac{E_1 I_{xx}}{M} , \text{ therefore,}$$

$$r_s = \frac{5W^2}{48\delta}$$

For the outer skins, the maximum bending stress σ_1 is

$$\sigma_1 = \frac{M}{I_{xx}} (t_2/2 + t_1)$$

For the core material, the maximum bending stress σ_2 is

$$\sigma_2 = \frac{M}{I_{xx}} \frac{t_2}{2} \frac{E_2}{E_1}$$

The transverse shear stress τ_{v_2} in the core at the neutral axis
is

$$\begin{aligned} \tau_{v_2} &= \frac{RAy}{I_{xx}b} \\ &= \frac{\frac{W_D W}{2} \left[b' t_1 \frac{(t_1 + t_2)}{2} + b \frac{E_2}{E_1} \frac{t_2}{2} \frac{t_2}{4} \right]}{I_{xx}b} \\ \tau_{v_2} &= \frac{W_D W \left[2t_1(t_1 + t_2) + \frac{E_2}{E_1} t_2^2 \right]}{8I_{xx}} \end{aligned}$$

The transverse shear at the bond line (τ_{vB}) is

$$\tau_{vB} = \frac{Rbt_1 \frac{(t_1 + t_2)}{2}}{I_{xx}b}$$

$$= \frac{\frac{W_D W}{2} \frac{(t_1 + t_2)}{2} t_1}{I_{xx}}$$

$$\tau_{vB} = \frac{W_D W t_1 (t_1 + t_2)}{4I_{xx}} \neq \tau_{v2} \text{ at } \frac{E_2}{E_1} \ll 1$$

Trial sandwich panel design No. 1: assume a sandwich panel having two outer PVC plastic skins bonded to a 2 lb/ft³ polyurethane foam core.
Let

$$E_1 = 2 \times 10^5 \text{ psi (at } 160^\circ\text{F)}$$

$$E_2 = 5 \times 10^2 \text{ psi}$$

$$t_1 = 0.040 \text{ inch}$$

$$L = 45 \text{ inches}$$

$$W = 15 \text{ inches}$$

$$b = 1 \text{ inch (unit strip)}$$

$$D = 0.347 \text{ psi}$$

$$\delta = 0.25 \text{ inch}$$

$$R = 2.603 \text{ lb}$$

$$M = 9.759 \text{ in-lb}$$

$$I_{xx} \geq 4.575 \times 10^{-3} \text{ in}^4$$

Evaluating stresses,

$$\tau_1 = 552 \text{ psi} - \text{safe for PVC at } 160^\circ\text{F}$$

$$\tau_2 = 1.17 \text{ psi} - \text{safe for polyurethane foam}$$

$$\tau_{v2} = 5.44 \text{ psi} - \text{safe for polyurethane foam}$$

Approximate cost factors in 45" x 15" panel:

| | <u>\$</u> |
|-------------------------------------|-------------|
| PVC skins - 2.34 lb at \$0.50/lb | 1.17 |
| PU foam core - 0.34 lb at \$0.70/lb | 1.24 |
| Adhesive - 0.59 lb at \$1.00/lb | <u>0.59</u> |
| Cost per panel | 2.00 |
| Cost per ft ² | 0.427 |
| Cost per M ² | 4.59 |

Trial sandwich panel design No. 2: assume a sandwich panel having two outer steel skins bonded to a rigid polyurethane foam core. Let

$$E_1 = 3 \times 10^7 \text{ psi}$$

$$E_2 = 5 \times 10^2 \text{ psi}$$

$$t_1 = 0.010 \text{ inch}$$

$$t_2 = 0.25 \text{ inch}$$

$$L = 45 \text{ inches}$$

$$W = 15 \text{ inches}$$

$$b = 1 \text{ inch}$$

$$D = 0.347 \text{ psi}$$

$$W_D = 0.347 \text{ lb/in.}$$

$$\delta = 0.25 \text{ inch}$$

$$R = 2.603 \text{ lb}$$

$$M = 9.759 \text{ in-lb}$$

$$I_{xx} = 3.382 \times 10^{-4} \text{ in}^4$$

$$\tau_1 = 3,900 \text{ psi} - \text{safe for steel}$$

$$\tau_2 = 0.06 \text{ psi} - \text{safe for polyurethane foam}$$

$$\tau_{v2} = 10.0 \text{ psi} - \text{safe for foam at } 4 \text{ lb/ft}^3; \text{ density at } E_2 = 10^3 \text{ psi, getting marginal for 2 pcf PU foam}$$

However, since the panel construction as configured appears adaptable to a 4 ft x 8 ft module, the strip beam will be analyzed in the simply supported 48-inch dimension. After calculation:

$\sigma'_1 = 39,890 \text{ psi}$ - marginally high for long-term steel loading

$\sigma'_2 = 1.24 \text{ psi}$ - safe for polyurethane foam

$\sigma'_{v2} = 32.0 \text{ psi}$ - foam will fail unless density is increased

The panel would need to be supported at intervals to resist transverse shear in foam.

Consider then a wood frame supporting structure under the substrate such that the maximum span, $W_1 = 16$ inches due to symmetry, only half the beam length need be studied, for which is found,

$\sigma_1'' = 3,750 \text{ psi}$ - safe for steel

$\sigma_2'' = 0.12 \text{ psi}$ - safe for foam

$\sigma_{v2}'' = 12.9 \text{ psi}$ - safe at 4 lb/ft^3 density

Approximate cost factors, 4 ft x 8 ft panel (2.97 M^2):

| | <u>\$</u> |
|-------------------------------------|-------------|
| 2 steel skins - 26.1 lb at 25¢/lb | 6.52 |
| 4 pcf PU core - 2.7 lb at \$0.70/lb | 1.85 |
| Adhesive - 1.0 lb at \$1.00/lb | <u>1.00</u> |
| Total for 4 x 8 - 29.8 lb | 9.41 |
| Cost per ft^2 | 0.294 |
| Cost per M^2 | 3.17 |

Approximate cost of support structure and foundation:

| | |
|--|-------------|
| 2 x 4's and 2 x 3's | 6.00 |
| Nails | 0.25 |
| Paint | 0.10 |
| Lag bolts | 0.25 |
| Concrete foundation posts | <u>1.00</u> |
| | 7.60 |
| Cost per M^2 | 2.56 |
| Total cost/ M^2 for substrate, support, and foundation | 5.73 |

Trial sandwich panel Design No. 3: If the steel skin/polyurethane foam core concept of sandwich panel design No. 2 is modified by increasing the moment of inertia, then possibly the core cost can be reduced by a return to a 2 lb/ft³ density foam and the support structure cost can be reduced by wider joist spacing. Therefore, let

$$E_1 = 3 \times 10^7 \text{ psi}$$

$$E_2 = 5 \times 10^2 \text{ psi}$$

$$t_1 = 0.010 \text{ inch}$$

$$t_2 = 0.375 \text{ (3/8) inch}$$

$$w_D = 0.347 \text{ lb/in}$$

$$I_{xx} = 7.413 \times 10^{-4} \text{ in}^4$$

Considering the 16-inch span spacing of design No. 2:

$$\tau_{v2} = 8.7 \text{ psi} - \text{safe for 2 pcf polyurethane foam}$$

But it appears that the spacing cannot be widened. The cost saving, however, for a 4 ft x 8 ft substrate would be \$0.47, \$0.015/ft², or \$0.16/M². Weight per panel would also be reduced by 0.7 pound.

If, however, t_2 were increased to 0.50 (1/2) inch, then,

$$I_{xx}' = 1.301 \times 10^{-3} \text{ in}^4$$

and in the above 16-inch span:

$$\tau_{v2}' = 6.6 \text{ psi} - \text{safe for foam}$$

Considering a supporting structure having 24-inch rib spacing instead of the 16-inch spacing:

$$\tau_{v2}'' = 9.9 \text{ psi} - \text{safe for 2 pcf foam}$$

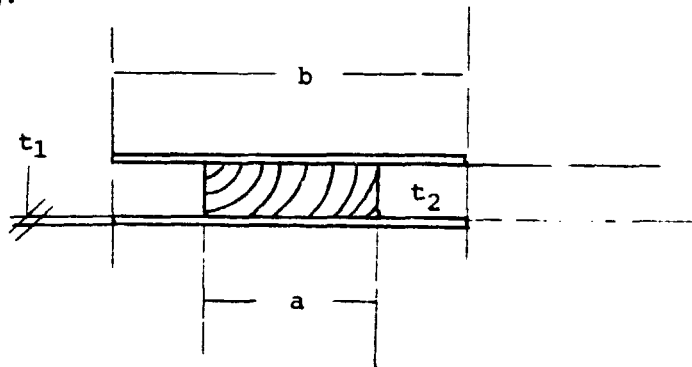
The cost of the substrate remains the same as in design No. 2 (\$3.17/M²), but the support structure is reduced by \$1.10, or \$0.37/M².

Approximate cost factors, 4 ft x 8 ft panel (2.97 M²):

| | \$ |
|---|------|
| Cost/M ² | 3.17 |
| Cost/M ² for support structure and foundation | 2.17 |
| Total cost/M ² for substrated, support, and foundation | 5.34 |

Trial sandwich panel design No. 4: assume a sandwich panel having two outer steel skins bonded to a grid of 1/2" x 2" wood (pine or fir at 25¢/board foot) at 2-inch spacing in the long direction and support structure rib spacing in the short direction. From design No.3, let span spacing be three beams at 32-inch spacing:

$$\begin{aligned}
 E_1 &= 3 \times 10^7 \text{ psi} \\
 E_2 &= 1.2 \times 10^6 \text{ psi} \\
 t_1 &= 0.010 \text{ inch} \\
 t_2 &= 0.50 \text{ inch} \\
 D &= 0.347 \text{ psi} \\
 a &= 2.00 \text{ inch} \\
 b &= 4.00 \text{ inch}
 \end{aligned}$$



$$I_{xx} = 6.036 \times 10^{-3} \text{ in}^4 \text{ (1.509} \times 10^{-3} \text{ at unit width)}$$

$$\begin{aligned}
 \tau_{v_2}' &= 28.03 \text{ psi} - \text{safe for wood} \\
 \tau_{1'}' &= 6,050 \text{ psi} - \text{safe for steel} \\
 \tau_{2'}' &= 240 \text{ psi} - \text{safe for wood}
 \end{aligned}$$

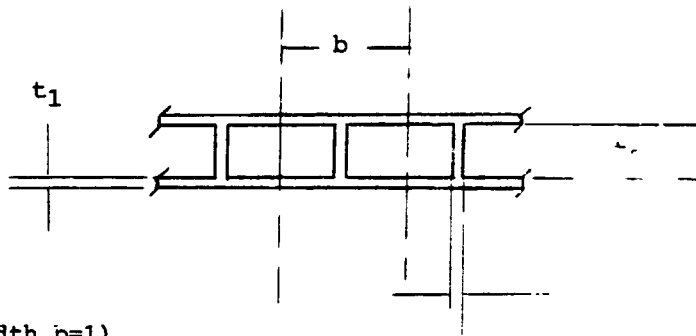
| | |
|---|-------|
| Cost factors for 4 x 8 panel: | \$ |
| Steel skins | 6.52 |
| Wood slats - 10 board feet at 25¢/bd ft | 2.50 |
| Adhesive | 1.00 |
| | 10.01 |
| Cost/ft ² | 0.313 |
| Cost/M ² | 3.37 |

The support structure would be as in design No. 3:

| | <u>\$</u> |
|---|-----------|
| Cost/M ² | 2.17 |
| Total cost/M ² for substrate, support, and foundation | 5.54 |

Trial sandwich panel design No. 5: assume a sandwich panel of two steel skins bonded to a styrene grid core of 1-inch spacing. Let

$$\begin{aligned} E_1 &= 30 \times 10^6 \text{ psi} \\ E_2 &= 3 \times 10^5 \text{ psi} \\ t_1 &= 0.010 \text{ inch} \\ t_2 &= 0.50 \text{ inch} \\ a &= 0.05 \text{ inch} \\ b &= 1.00 \text{ inch} \end{aligned}$$



In a 1-inch section (of width $b=1$),

$$I_{xx} = 1.306 \times 10^{-3} \text{ in}^4$$

Using the 32-inch support frame spacing (see design No. 4):

$$\begin{aligned} \sigma_{v2} &= 261 \text{ psi} - \text{safe for styrene} \\ \sigma_1 &= 6,938 \text{ psi} - \text{safe for steel} \\ \sigma_2 &= 68 \text{ psi} - \text{safe for styrene} \end{aligned}$$

Since the stress levels are conservative, try two 48-inch spans:

$$\begin{aligned} \sigma'_{v2} &= 413 \text{ psi} - \text{safe for styrene} \\ \sigma'_1 &= 19,497 \text{ psi} - \text{maximum allowable for steel} \end{aligned}$$

Construction is safe:

$$\text{Radius of curvature, } r'_s = 392 \text{ inch; } 93.75 \text{ inches: safe}$$

Approximate cost factors:

Styrene -

Volume = $75.56 \text{ in}^3/\text{M}^2$ at \$0.35/lb

Cost/ M^2 = \$1.14

This is more expensive than designs 2, 3, or 4.

| | |
|---|-------------|
| | <u>\$</u> |
| Steel skins, 0.01 in. | 6.52 |
| Styrene grid | 3.38 |
| Adhesive | <u>1.00</u> |
| | 10.90 |
| Cost/ M^2 | 3.67 |
| Cost/ M^2 for support structure, 48-inch spans | 2.02 |
| Total cost/ M^2 for substrate, support, and foundation | 5.69 |

A summation of the cost analyses resulting from this study appears in the cost comparison (Table 17) and, although the figures are estimated, demonstrates the feasibility of constructing substrates and solar cell modules well within the 1980 cost goal of \$14/ m^2 , including support frame.

This study indicates that sizeable cost reductions over "single sheet" substrates may be achieved through the use of basic structural engineering. For the materials examined, sandwich panel designs provided the most effective use of the construction materials. When the cost per square meter figures are compared, however, the single sheet substrates based on wood products still appear to be much more promising than structurally engineered composites. The following is a comparison of the lowest costing products discovered in each class of construction materials surveyed to date:

| <u>Material Class</u> (Lowest Costing Product Meeting Deflection Spec.) | <u>Cost, \$/m²</u> (Without Frame or Supports) (1978 Dollars) |
|---|--|
| Plastic; Arcc Dylark 238 | \$ 5.70 |
| Metal; Hot rolled steel | \$ 4.52 |
| Structural composites | \$3.17 |
| Ceramics: Soda-Lime Glass | \$3.13 |
| Wood Products (Strandboard, Hardboard, etc.) | \$ 1.51 (estimated) |

Single sheets of glass, as would be used in superstrate designs, are approximately equivalent in cost to the structurally engineered products examined in this study. Wood products, however, are less than half the cost. Quarter inch thick plywoods and chipboards that would be recommended for LSA cost out at approximately \$1.51/m². Hardboard products with densities in excess of 50 lbs/ft³ are available at costs close to \$1.07/m² and meet the deflection resistance criterion with a single center reinforcing strut in the standard 15 x 45 inch design.

Strandboard, a not yet commercial wood product, is expected to have a modulus in excess of chipboard and a cost approaching \$1.29/m² (1978 dollars) at a 1/4 inch thickness.

An additional advantage to the particle, flake and strandboard products is that they may be prepared by a platten press or lamination process that will permit the required reinforcing ribs and trusses to be molded in during manufacture. It is expected that future engineering efforts to discover the most cost effective substrate will employ this approach.

XII. ALTERNATE POTTANTS

Preliminary investigations of candidate potting compounds other than EVA have also been conducted during the past year. These compounds represent "second choice" materials in the event that the EVA pottant appears to be unsuitable for a particular module design or process. This, hopefully, will also result in a few alternate choices of pottant for solar module manufacturers who may be pursuing different fabrication concepts than those emphasized in this report.

The criteria for the selection of alternate pottants are essentially the same for EVA; high transparency, processability, weatherability (or the potential to be made weatherable) and attractive cost.

a. EPDM Pottant

Preliminary investigations of an EPDM (ethylene-propylene diene rubber) base polymer have been started, the first criteria being transparency and extrudability. Samples of NORDEL rubber, numbers 1320, 1560, 2522, and 2744 have been received from DuPont Chemical Company. These are their recommended starting compounds. Extrusion was attempted with 1320 and 2522 only, the other two compounds being too hazy to give good transmission values. The laboratory sized Brabender 3/4 inch extruder was used equipped with a film die set for about 15 mils thickness. Both EPDM compounds extruded smoothly at barrel temperatures of 175°F (80°C) and a die temperature of 225°F (107°C).

No tackiness or handling problems were encountered with the extruding melt, and it was taken up between sheets of silicone release paper as with EVA. Although the extrusion temperatures are hotter for EPDM than EVA, no problems in formulating a successful cure and stabilization system for the higher temperature are anticipated.

The following page gives typical formulae and cured properties for NORDEL rubbers as published by DuPont Chemical Co. Samples of EPDM from the only other manufacturer, Exxon Chemicals, will also be evaluated.

TRANSPARENT NORDEL®

RECOMMENDED STARTING FORMULATIONS

| | | | | | |
|------------------------|-----|-----|-----|------|-----|
| NORDEL® 1560 (pellets) | 50 | 50 | 50 | 50 | 50 |
| NORDEL® 2522 | - | - | 50 | - | - |
| NORDEL® 2744 | 50 | 50 | - | 50 | 50 |
| Tufflo 6204 | 30 | 30 | 30 | 30 | 30 |
| Cab-O-Sil | 15 | 15 | 15 | 16.8 | 15 |
| Stearic Acid | 1 | 1 | 1 | 1 | 1 |
| Di-Sup R | 3 | 6 | 6 | 7 | 7 |
| Irganox 1076 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |

CURED PROPERTIES

Stress/Strain

| <u>Original</u> | 2'/400°F | 2'/400°F | 2'/400°F | 24'/320°F | 24'/320°F |
|--------------------------|----------|----------|----------|-----------|-----------|
| 100% Modulus, psi | 200 | - | 140 | 210 | 210 |
| 200% Modulus, psi | 350 | - | 260 | 500 | 500 |
| Tensile Strength, psi | 3060 | 0 | 670 | 1060 | 1030 |
| Elongation, % | 750 | - | 420 | 450 | 450 |
| Hardness | 57 | - | 45 | 60 | 69 |
| <u>Aged 3 days/212°F</u> | | | | | |
| 100% Modulus, psi | 220 | 0 | 170 | 220 | 200 |
| 300% Modulus, psi | 380 | - | 330 | 600 | 530 |
| Tensile Strength, psi | 3210 | - | 770 | 1190 | 1240 |
| Elongation, % | 750 | - | 480 | 430 | 420 |
| Hardness | 61 | - | 48 | 61 | 62 |

Bubbles
in
Slabs

Nordel 1320 was chosen for study as a baseline EPDM compound due to its high optical transmission and its low melt viscosity. The following formulation was devised and a laboratory investigation started:

Baseline EPDM Formulation

| <u>Compound</u> | <u>Parts</u> |
|--------------------|--------------|
| Nordel 1320 (EPDM) | 100 |
| Lupersol 231 | 1.0 |
| Cab-O-Sil MS-7 | 3.0 |
| Tinuvin 770 | 0.1 |
| Cyasorb UV-531 | 0.3 |
| Goodrite 3114 | 0.2 |

Compounding was performed on a differential two roll mill, the polymer sheeted off, and chopped in a rotary mill with the aid of liquid nitrogen. The ground material was then fed into the hopper of the Brabender laboratory extruder and converted to sheet. This polymer, being a rubber, is more difficult to handle than the EVA copolymers. The melt viscosity is higher, the extrusion speed lower and higher temperatures are required for extrusion. "Scorch" (premature crosslinking) also must be taken into account at the higher extrusion temperatures required (225°F). The use of Lupersol 231 in this formulation presents no problems with bubble formation during vacuum bag processing. This is probably due to the diene functionality of the resin which is much more reactive with the peroxide at lower temperatures. Lupersol 101 has not been found to be a suitable curing agent for this polymer (low gel contents). The large module presented no difficulties in vacuum bag encapsulation and is currently undergoing JPL thermal cycle qualification testing.

b. Aliphatic Urethane

To date, our surveys have identified only one castable 100% solids aliphatic urethane system. This is available from H. J. Quinn & Co., Malden, Mass. The isocyanate prepolymer is designated Q-621 and is a transparent liquid of 3,400 centipoise viscosity and an equivalent weight of 520 -540. It may be cured with a variety of diols. Quinn recommends their polyether diol designated Q-5829 or Q-626. After mixing the two part system, the pot life is approximately 3 hours at 70°F. Cure conditions are 2 hours at 200°F or about 6 hours at 120°F. The cure rate is adjustable and depends on the quantity of catalyst used. The cost of the mixed system is estimated to be in the order of \$1.30 per pound.

Test modules have been prepared from this system at Springborn Laboratories. The urethane is not found to be any more difficult to handle than any other liquid casting system. One precaution, however, is that the mixed or unmixed system must be free of water and kept isolated from atmospheric humidity due to the destructive effect of water on the isocyanate. The hydrolysis reaction of the isocyanate prepolymer also produces carbon dioxide which may result in bubbles appearing in the potting. The modules are undergoing thermal aging tests to determine the oxidative stability. A slight yellowness can be noticed after 100 hours of aging at

90°C. Specimens are in preparation for RS/4 exposure to determine the relative UV resistance of this baseline compound. Other manufacturers are also being pursued. It is believed that Mobay and Spencer/Kellog companies may also have a comparable product. Lord-Hughson and Naftone companies also are said to be developing product lines in this area.

Eleven cell mini-modules will be prepared and submitted for the thermal cycle qualification test in the near future.

XIII. ABRASION RESISTANT COATINGS

In substrate design modules, the silicon solar cell will probably be encapsulated with ethylene/vinyl acetate copolymer, an elastomeric copolymer. To provide 20 year life not only does this pottant contain UV absorber but it is protected with an acrylic film (Korad 201R) also containing UV absorber.

Polymethymethacrylate (Korad 201R) is not scratch or abrasion resistant. Over the years, wind blown dust could mar the surface of the outer acrylic film decreasing light transmission and may consequently decrease the electrical power output.

To avoid this loss of power a survey has been made of abrasion resistant and low friction (high slip) films. The rationale is the harder or (perhaps) the more slippery, the more scratch resistant. Polysilicates provide the harder film; fluorocarbons the lower friction films. However, it is doubtful that fluorocarbon films would provide anywhere near the scratch and abrasion resistance of the hard polysilicates.

Polysilicates

Polysilicates have been in use for many years to protect acrylic and polycarbonate glazing in aircraft. Owens-Illinois' glass resin and DuPont's Abcite (a fluorocarbon-silicate) are early examples of these coatings.

The following companies now produce, or are investigating polysilicate coatings.

- Dow Corning
- G.E.
- E. I. DuPont
- Rohm & Haas
- 3M
- American Optical
- Owens Illinois
- Berg

These coatings, polysilicates or fluorocarbon-silicate compounds, are applied in extremely thin layers and yield hard transparent and weather resistant coating. These coatings are expected to find use in solar modules for the following reasons:

- a. Prevention of abrasion by wind blown sand.
- b. Reduce dust accumulation.
- c. Cleanability; the coatings are hard, oleophobic and hydrophobic and consequently should be more easily cleaned than other surfaces.
- d. They should retard the rainwater extraction losses of any low molecular weight components present in the polymer outer cover such as antioxidant.
- e. Serve as a weathering barrier to provide additional protection to the outer cover.
- f. May provide additional UV absorber protection, depending on formula.

ARC Coating (Dow Corning)

An article, in Process Engineering News, June 1977, describes in depth the Dow Corning ARC coating;

"A new silicone resin coating material has been designed to give superior abrasion protection to polycarbonate, acrylics and other transparent plastics. The Dow Corning ARC coating is available from Dow Corning Corp., Midland, Mich. Besides acrylic and polycarbonate, ARC coating reportedly has been successfully applied to allyl diglycol carbonate (such as PPG's CR-39), cellulose, styrenics and unsaturated polyester without need for a film-forming primer."

"Abrasion test results: Taber abrasion tests on flat samples were performed using Taber Abraser CS10F wheels under 500-gm load. Uncoated PC showed 25% increase in haze (per ASTM D-1003-61) and uncoated acrylic 15% increase after 100 cycles, while an uncoated CR-39 casting increased 7.5% in haze after 500 cycles. These same three materials with 3-5 micron ARC coating all showed less than 1% increase (0.7-0.9%) in haze after 500 abrasion cycles. (For comparison, Lucite AR, DuPont's acrylic sheet coated with Abcite fluorocarbon-silicate copolymer, showed 8% more haze after 500 cycles. Window glass reportedly increases 0.3-0.4% in haze by this test.)"

"Pencil hardness of acrylic or CR-39 with 2.5-3.0 micron ARC coating is said to be 8-9 H, compared with 3-4 H for ARC-coated PC. Company spokesmen say that a 5-micron ARC coating on PC can obtain a pencil hardness of 8-9 H."

According to Dow Corning, one advantage of ARC over certain other protective coating materials is its high hydrolytic stability. Lab exposure to elevated temperature and high humidity reportedly has no significant effect on the abrasion protection afforded by ARC, though it does on other coatings. ARC also retained its properties better in tests with the Atlas carbon-arc Weather-O-Meter. (Company

sources note that while ARC is itself nearly transparent to UV light and very weatherable it will not be suitable for long-term exterior service on substrates which are not themselves UV stable.)

In addition to abrasion resistance, ARC coatings reportedly provide considerable protection against chemical and solvent attack. For example, PC reportedly is quite prone to stress cracking after chemical exposure. Yet Dow Corning tests are said to show that ARC-coated PC and acrylic suffer no damage from exposure to a number of common solvents, including aromatics, chlorinated hydrocarbons, ketones and alcohols, plus antifreeze, motor oil, gasoline, etc.

Adhesion of ARC has been tested by three pulls of tape across a crosshatched grid pattern, showing no coating removal.

ARC is supplied as a liquid silicone resin of low-to-medium viscosity. It can be applied by dip, spin, flow or spray-coating techniques. Various chemical pretreatments may be needed to condition the substrate surface, depending on the plastic type and cleanliness. (A "clean-room" environment is required in applying the coating.)

The coating is oven cured at temperatures as low as 150°F. The cure time is such as to require batch operations rather than permitting continuous web processing. ARC is not considered useful on highly flexible substrates - i.e., films - or in applications requiring extensive elongation in processing or end use. ARC itself has only 1-1-1/4% elongation.

Raw material cost for a 3-5 micron coating on one side of a substrate is pegged at around 2¢/sq ft,. Users of ARC must obtain a license from Dow Corning involving payment of a running royalty.

One licensee, Air-Lock, Inc., Milford, Conn., has coated space helmets for astronauts, instrument panel covers, watch crystals, safety face visors, recreational face shields and auto trim.

The potential of this material was recently investigated at JPL. Half of a single cell module (Masonite - Super Dorlux - substrate-ethylene/vinyl acetate pottant/Korad 201R outer film was coated by Dow Corning with their ARC material. The coated module was abraded by hand with a brillo pad. Only the uncoated half was scratched.

We will be working with Airlock Corp., licensee of Dow Corning, in putting on the ARC coating onto one cell modules.

G.E.

General Electric has two polysilicate systems. One, SHC 1100, is used without a primer and is still experimental. The other system uses a Rhople/emulsion primer, SHP-100 and a silicone hardcoat, SHC-1000.

The coating procedure is as follows:

PRIMER

- (1) In a well ventilated area, preferably having a filtered (dust free) air supply, apply a 4% (solids) primer solution to the part(s) by dip or flow coating. Use caution because the primer solvent(s) may be hazardous.
- (2) Primer should drain and air dry for 20-30 minutes. Be sure to remove dip tank or tray as soon as primer is applied. Do not expose uncured primer films to solvent vapors.
- (3) Cure primer coat for 30 min. at 120-125°C. Use an oven having strong mechanical (forced) air circulation and fast heat recovery.
- (4) Remove sample(s) and cool to room temperature before applying SHC. This is a critical step -- do not coat parts warm as optical defects can result.

COATING

- (5) Using the same ventilated area* as in Step 1, dip or flow coat the parts with Silicone Hard Coat (SHC).
- (6) Coating should drain and air dry for 10-30 minutes. Be sure to remove dip tank or tray as soon as coating is applied. Do not expose uncured Hard Coat films to solvent vapors.
- (7) Cure the SHC resin for 30-60 minutes at 120-125°C. Use the same oven type as in Step 3.
- (8) Cool to room temperature. Parts prepared with Silicone Hard Coat are ready for service.

*Relative humidity in the coating area should not exceed 50% R.H.

The top coat (SHC-100) contains a UV stabilizer which they believe reacts with the silicone and thus has reduced extractibility.

One cell modules will be sent to Dr. W. Kray of G.E. for polysilicate coating.

The characteristics of their materials are shown on the following charts.

| | |
|------------------------------|--|
| <u>Compound</u> | SHC-1000 |
| Manufacturer | General Electric |
| Type | Silicones |
| Substrates | PC, acrylic-primer |
| Hardness | Depends on substrate |
| <u>Process</u> | |
| 1) Primer | Rhoplex SHP-100 |
| 2) Bake | 120°C |
| 3) Application | Dip, flow spray-possible |
| Thickness | Primer 0.05 mils Top coat 0.2 mils 0.25 mils total |
| Initial cost/ft ² | .09 - .10 |
| Weatherability | PC 5 years est. acrylic excellent |
| License | No |
| Films | Yes |
| Sell Solution | Yes |
| Remarks: | Delaminates from PC as PC degrades. The top coat should act as a soil release since it resists painting. |

| | |
|-----------------|---|
| <u>Compound</u> | SHC-1000 |
| Manufacturer | G.E. |
| Type | Silicone |
| Substrates | Acrylic - Plexiglas S trouble w/molded/ Aeriview extruded unless primed |
| Hardness | Depends on substrate |

| | |
|------------------------------|-------------------------------|
| <u>Process</u> | |
| 1) Primer | No-Yes others cost acrylic |
| 2) Bake | 120°C |
| 3) Application | Dip, flow, spray |
| Thickness | 0.2 - 0.25 mils |
| Initial cost/ft ² | 0.9 - .10 |
| Weatherability | Excellent - 3 years PC |
| License | No |
| Film | Yes |
| Sell Solution | No |

E. I. DuPont

E. I. DuPont has an abrasion resistant, silicate-type coating put on by a dip process. Harry Begg, Plant Manager, tried to coat pieces of Tedlar UT and Korad 201R but could not because of too great a film flexibility. Their coating can only be applied to a rigid substrate.

Rohm & Haas

Rohm & Haas sells polycarbonate with an abrasion-resistant coating. They also sell ARC 360 for the interior of aircraft windows. No specific information was provided although they are willing to coat samples for us on an experimental basis.

3M

3M has a coating with similar abrasion properties to ARC. They will not sell solution but will coat roll stock only. They would not provide cost data. Their present technology has certain flaws since it does not stick well to acrylic. On cellulose acetate Butyrate after 6-9 months in Florida, the coating is cracking and checking.

American Optical

Gordon Curtis informed us that AO is producing an abrasion resistant coating called A050M. It is applied by dipping to a thickness of 3 nm with a bake temperature of 165-200°F. It is designed for polycarbonate.

AO puts on a Dow Corning ARC film in their Brattleboro operation.

In their abrasion test they use a pad with abrasive and grind in water.

On a scale of 1 - 10 (10 best) they rate the following coatings for abrasion resistance.

| <u>Material</u> | <u>Rating</u> |
|------------------|---------------|
| Berg Vac deposit | 7 |
| A050M | 4 |
| Dow Corning Akc | 4 |
| DuPont | 4 |
| G.E. | 3 |

Owens Illinois

According to Don Gagnon their Glass Resin 650 (one of the earliest in this field) coated on metal has undergone 12 years exposure in Florida without change.

Cost is 2.3¢/ft² at 0.3 Mils thick. Applications have included polycarbonate and acrylic in aircraft. Transparency is improved 1-3%. The material is a methyl silicon homopolymer and as coated is 89% silica. Characteristics are as follows:

| | |
|----------------------|--|
| Compound | Glass resin 650 |
| Manufacturer | Owens Illinois |
| Type | Polysilicate |
| Substrates | Polycarbonate Acrylic |
| Hardness | |
| <u>Process</u> | |
| 1) Primer | No |
| 2) Bake | 80-90°C, with catalyst 5'-2 hrs. |
| 3) Application | Spray or dip |
| Thickness | 0.3 mils |
| Cost/ft ² | 0.023 |
| Weatherability | Good - 12 years on metal if Florida - no change |
| Films | No |
| Sell solution | |
| Remarks | Claim abrasion equal to ARC |

Berg Industries

Mr. Berg, Ontario, Canada, indicates that his silica coating is vacuum deposited on lenses. The coating is about 3 nm thick with about 3 nm embedded into the plastic. Thinner coatings may be possible. He claims a high degree of hardness, excellent impact and antistatic properties. Capital cost is estimated at about \$700,000; coating costs are high.

XIV. CONCLUSIONS

1. Appropriately compounded ethylene-vinyl acetate copolymer (EVA) appears to be a useful pottant for the low cost encapsulation of solar modules. Although strict correlations cannot be made between the results of artificial accelerated testing and actual outdoor performance, the prognosis is encouraging when test results are compared to the performance of other materials. It would be desirable to continue with experiments in stabilization, lifetime diagnosis and field trials of actual modules.
2. Vacuum bag processing appears to be one of the most promising methods of solar cell encapsulation. This method employs assemblies of pre-cut materials with long shelf life and a complete fabrication time of half an hour to forty five minutes. This method is also ammenable to automated production and the finished modules require no further cure cycle.
3. Good methods have been devised for the production of clear EVA sheet, simple blending and extrusion give excellent results. The pigmented composition needs further development, however. The masterbatch technique is satisfactory for laboratory scale investigation, but cannot be used successfully on commercial scale due to the length of time required for blending on the mill roll and the expense of grinding the final product with liquid nitrogen.
4. Good results have been obtained to date with the use of silane primers to promote glass and hardboard substrates have exceeded the cohesive strength of the polymer at strengths of 20 to 30 pounds per inch of width. The best overall primer discovered to date is hydrolyzed Dow Corning Z-6030 (our Number A8330B). More work in this area would be desirable to improve the predictability of bonding as some of the results are variable.
5. A hardboard product - Super Dorlux (Masonite Corporation) has been found to be useful as a substrate material in having a good balance of low cost and adequate mechanical properties. In order to become a fully usable product a certain amount of development remains. One problem is that of surface cohesion. When a polymer bond is forced apart, the fibrous surface of the hardboard is what yields; the bond strength is, therefore, limited by the surface property of the board. A more serious problem is that of humidity and water effects. Hardboard sheets and modules prepared with hardboard substrates tend to warp with fluctuations in humidity and swell badly at the edges in contact with

liquid water. A waterproofing treatment of some variety will be required to reduce these effects and retard the influx of water vapor to the surface.

6. Outdoor weathering experiments, including both natural exposure to desert sun and EMMAQUA, were performed on tensile specimens and modules prepared from a variety of potentially useful encapsulation materials. The most resistant materials were found to be the fluorocarbons, especially Kel-F resin and FEP Teflon film. These polymers showed the least amount of change to any condition. Tedlar film (100BG30UT) was found to decay badly in optical transmission and degraded to the point of fracture in the module system exposed to EMMAQUA. The most resistant of the low cost polymers were the acrylic materials, retaining both excellent optical properties and acceptable mechanical properties. Outer covers based on acrylic polymers should perform well.
7. Low modulus pottants are required for the encapsulation of solar cells in order to relieve stresses resulting from thermal excursions. The low modulus is also accompanied by a low surface hardness which gives rise to a problem of soiling on the outer surface. In order to retard the soiling effect, maintain high transmission, and protect the underlying pottant a high modulus high surface hardness coating is required. In order to extend the useful working life of the module, the function of UV screening has also been imposed on the outer cover. The two materials of current interest for this function are Tedlar 100 BG 30 UT and the multipolymer acrylic Korad 201R. Both are found to bond successfully to EVA, have high surface hardness, provide UV screening and have high transparency. Tedlar has shown very variable performance under outdoor exposure and more field experience is necessary to qualify the usefulness of this material. Korad, in addition to being less expensive than the Tedlar, has a better prognosis for long term weather stability. The deficiency of Korad is that the UV stabilizer exudes from the film and becomes lost after a few years. Development work is required to prevent this loss.
8. Encapsulation with EVA has been shown to provide good long term resistance to corrosion in a severe salt spray environment. Aluminum, galvanized steel and copper were particularly unaffected and remained shiny after almost eleven weeks of salt fog at 35°C. Mild steel was the most affected, showing signs of corrosion after about three weeks. In contrast, the control specimens began to corrode in a matter of hours after exposure.

9. Experiments with "scrim" materials have found that the best selection to date is "Craneglass 230", a non-woven glass cloth manufactured by Crane Co., Dalton, Mass. This cloth is available in a variety of thicknesses at low cost. The 5 mil thickness costs \$0.0078/ft². The use of this scrim has been found to: (a) successfully replace a layer of EVA pottant; (b) prevent the flow of the pigmented layer; (c) provide a fixed distance between the cell and substrate; (d) aid in vacuum evacuation; and (e) lower the fabrication cost.
10. Engineering studies of materials and designs for the substrate function indicate that the cost goals are achievable with a variety of approaches. Grid and sandwich panel constructions appear to be feasible with the use of raw materials such as steel, fir slatting and low density polyurethane foam. The lowest cost found so far is for a steel polyurethane sandwich construction, which, including frame, foundation and supports adds up to a cost of \$5.34/m². The inclusion of costs for pottants and outer covers brings the total to \$6.53/m² (1975 dollars). This is encouraging and well within the total allocation for encapsulation of \$8.00/m² (1975 dollars, including support frame).
11. Alternate pottants to the EVA system are currently under investigation, but further evaluation of these materials will be required before they reach a state of industrial readiness. The two materials being emphasized at this point are aliphatic polyurethane and EPDM (ethylene/propylene-diene monomer rubber).
12. Commercial abrasion resistant coatings have been found to provide an extremely hard and abrasion resistant surface to the Korad coated modules prepared to date. One of the more attractive is ARC manufactured by Dow Corning, Midland, Michigan. This coating may be applied at a cost of \$0.02/ft². These coatings also need more evaluation by field trials to fully assess their usefulness.

XV. FUTURE WORK

The following technical items will be included in the coming year's work:

1. Construction and testing of large numbers of single and double celled modules will be carried out for the purpose of more clearly defining fabrication techniques and further assessing the performance of the EVA pottant, when used in actual systems.
2. Experiments will be performed to define more adequately the heating rates and cure of the EVA during the vacuum bag encapsulation process and set of specifications will be written to aid module manufacturers in the production of modules of reproducible characteristics.
3. Studies of the ultraviolet stabilizers and antioxidants used to optimize the service life of the EVA pottant will continue with the aid of RS/4 sunlamp, EMMAQUA and natural weather exposure for evaluation.
4. More extensive work on the use of surface applied primers to generate high reliability bonds in critical areas will be conducted, with an emphasis on cost and industrial usability.
5. The concept of blending silane adhesion promoters directly into the EVA formulation will be reinvestigated to further assess if this approach is feasible.
6. Experiments will investigate the feasibility of incorporating a chemically bound and non-extractable UV absorber into an acrylic film vehicle. If successful, it is hoped that this approach will yield an outer cover with the best cost/performance as a protective film for the underlying pottant.
7. Experiments with chemical surface modification of acrylic outer cover materials will be conducted to improve hardness, abrasion resistance and resistance to water permeability.
8. Low cost abrasion resistant coatings will be investigated in the laboratory for efficiency and applicability to module manufacture.
9. The evaluation of EPDM (ethylene/propylene/diene rubber) as an alternative pottant to EVA will be continued. Formulation, compounding, extrusion and module construction will be continued to investigate the usefulness of this polymer.

10. Development work will continue on aliphatic urethanes as alternate pottants to the EVA system. Transparency, weatherability and cost will be emphasized in the selection of a manufacturer usable system that may be used as an alternate to the silicone casting products.
11. Studies will be conducted to assess the viability of wood and wood products (like hardboard and flakeboard) as substrate materials. Mechanical properties and resistance to liquid water and humidity will be considered.
12. A pourable polyvinyl chloride (PVC) plastisol compound will be developed as an alternate pottant for use in case encapsulation systems.
13. A poly-n-butyl acrylate pottant will be investigated also as an alternate material for casting systems.
14. A complete cost analysis will be performed on each candidate encapsulation system proposed.

APPENDIX

TABLES AND FIGURES

TABLE I

Ethylene - Vinyl acetate Copolymer Survey

| Compound | Vinyl Acetate % | Density (g/cc) | Tensile @ Break ⁽²⁾ (psi) | Elongation ⁽²⁾ @ Break (%) | Cost ⁽⁴⁾ (\$/lb.) |
|------------|-----------------------|-------------------|---|--|---------------------------------|
| EY 901-25 | 40 | 0.962 | 1200 | 700 | \$0.64 |
| EY 902-30 | 40 | 0.962 | 800 | 1,000 | \$0.64 |
| UE 654-35 | 33 | 0.954 | 660 | 870 | \$0.645 |
| UE 638-35 | 31 | 0.954 | 720 | 960 | \$0.635 |
| UE 646-04 | 28 | 0.949 | 1,100 | 770 | \$0.615 |
| Elvax 150 | 33 | 0.957 | 850 | 1,050 | \$0.575 |
| Elvax 240 | 28 | 0.951 | 1,050 | 900 | \$0.545 |
| Elvax 250 | 28 | 0.951 | 1,400 | 950 | \$0.545 |
| Elvax 260 | 28 | 0.955 | 2,800 | 1,000 | \$0.545 |
| Elvax 420 | 18 | 0.937 | 950 | 700 | \$0.545 |
| Elvax 350 | 25 | 0.948 | 1,600 | 900 | \$0.505 |
| Elvax 4260 | 28 | 0.955 | 2,700 | 1,000 | \$0.675 |
| Elvax 4320 | 25 | 0.947 | 750 | 900 | \$0.635 |
| Elvax 4355 | 25 | 0.952 | 2,800 | 1,000 | \$0.665 |

(1) Total integrated transmission, solar normalized, 350 - 800nm.

(2) ASTM Test D638; Type IV Specimen.

(3) Melt index figures obtained from ASTM Test D1238 E.

(4) Cost values listed for maximum quantity of material.
Prices shown in 1979 dollars.

TABLE I (Continued)

Ethylene - Vinyl Acetate Copolymer Survey

| Compound | Manufacturer | Composition | UV T _Z | Vis T _Z (1) | Refractive Index n _d | Average (3) (g/10 min) Equivalent Melt Index |
|------------|--------------|---------------|-------------------|------------------------|---------------------------------|---|
| EY 901-25 | USI | EVA | 74 | 86 | - | 7.5 |
| EY-902-30 | USI | EVA | 75 | 91 | 1.482 | 70.0 |
| UE 654-35 | USI | EVA | 78 | 84 | - | 48.0 |
| UE 638-35 | USI | EVA | 77 | 86 | - | 24.0 |
| UE 646-04 | USI | EVA | 77 | 85 | - | 25.0 |
| Elvax 150 | DuPont | EVA | 73 | 91 | 1.482 | 43 |
| Elvax 240 | DuPont | EVA | 66 | 89 | 1.485 | 43 |
| Elvax 250 | DuPont | EVA | 68 | 91 | 1.485 | 25 |
| Elvax 260 | DuPont | EVA | 68 | 86 | 1.485 | 6 |
| Elvax 420 | DuPont | EVA | 61 | 82 | 1.492 | 151 |
| Elvax 350 | DuPont | EVA | 73 | 87 | 1.489 | 19 |
| Elvax 4260 | DuPont | EVA/Acid Ter. | 67 | 87 | 1.485 | 6.0 |
| Elvax 4320 | DuPont | EVA/Acid Ter. | 67 | 91 | 1.486 | 150 |
| Elvax 4355 | DuPont | EVA/Acid Ter. | 67 | 91 | 1.482 | 6.0 |

(1) Total integrated transmission, solar normalized, 350 - 800nm.

(2) ASTM Test D638; Type IV Specimen.

(3) Melt index figures obtained from ASTM Test D1238 E.

(4) Cost values listed for maximum quantity of material.
Prices shown in 1979 dollars.

TABLE 2

PEROXIDE CURE VERSUS GEL CONTENT

ELVAX 150

| A8937 A - | A | B | C | D | E | F |
|------------------------|-----------|-------|-------|-------|-------|-------|
| Elvax 150 | 100 | 100 | 100 | 100 | 100 | 100 |
| Lupersol 101 | 1.5 | 1.0 | 0.75 | - | - | - |
| Lupersol 231 | - | - | - | 1.5 | 1.0 | 0.75 |
| Tinuvin 770 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| UV-531 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Irganox 1076 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 150 C/20 min Gel, % | 89.9% | 86.4% | 86.6% | 91.9% | 91.4% | 88.7% |
| 135 C/20 min Gel, % | - | - | - | 90.8% | 88.2% | 85.6% |
| A8937 B - | ELVAX 250 | | | | | |
| Elvax 250 | 100 | 100 | 100 | 100 | 100 | 100 |
| Lupersol | 1.5 | 1.0 | 0.75 | - | - | - |
| Lupersol 231 | - | - | - | 1.5 | 1.0 | 0.75 |
| Tinuvin 770 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| UV-531 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Irganox 1076 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 150 C/20 min Gel, % | 85.6% | 84.6% | 0 | 86% | 88.9% | 87.4% |
| 135 C/20 min Gel, % | - | - | - | 82.8% | 85.1% | 0 |

TABLE 3
ANTIOXIDANT STUDY
(with Lupersol 101)

| Notebook No. A9920 - | | | | Hours at 90°C | |
|--|-------------|-------------|---------------|---------------------------------------|--|
| Antioxidant | Level (phr) | Gel Density | Gel Content % | Thermal Stability Color _{a.} | Corrosion Effect on Copper _{b.} |
| 1. Goodrite 3114 ^{c.} | 0.2 | low | 17.6 | 1 | 2 |
| 2. Dilauryl Thiodipropionate | 0.2 | low | 42.9 | 1 | 1 |
| 3. Polygard | 0.2 | high | 78.5 | 1 | 1-2 |
| 4. Disteryl Thiodipropionate | 0.2 | high | 78.3 | 1 | 2 |
| 5. Irganox 1076 ^{c.} | 0.2 | high | 76.9 | 1 | 4 |
| 6. Naugard P | 0.2 | low | 69.4 | 1 | 1 |
| 7. Naugard P Irganox 1035 ^{c.} | 0.1 0.1 | low | 62.9 | 1 | 4 |
| 8. Irganox 1010 ^{c.} MD 1024 | 0.1 | high | 87.4 | 1 | 3 |
| 9. Control—no AO | 0 | high | 92 | 2 | 2 |

All formulations prepared by milling the antioxidant into a standard formulation of:

Elvax 150 100 phr
Lupersol 101 0.75 phr
Tinuvin 770 0.1 phr
UV-531 0.3 phr
Antioxidant () phr

Plaques prepared by compression molding and cured at 150°C for twenty minutes. Copper disc molded into plaque for corrosion effect.

a. Thermal evaluations performed by subjective assessment of color formation:

- | | |
|-----------------------|---------------------|
| 1. No color formation | 4. Noticably yellow |
| 2. Very light color | 5. Bright yellow |
| 3. Light color | |

b. Corrosion also determined by color of ring around copper molded into polymer.

c. Phenolic compound, possibly causing UV sensitization. Omitted from selection. Omitted for low gel content; No.'s 1, 2

Final selection: Naugard-P selected over Polygard (3) for better corrosion protection at 150°C thermal aging.

TABLE-4

ADHESIVE BOND STRENGTH EVALUATION
Average Bond Strength by ASTM D903 or ASTM D1876
(Pounds per inch of Width)

| Notebook No. | Test Specimen Materials | Primer | | | | |
|--------------|-------------------------------|----------|-----------|---------------------------|------------------------|-------------------------|
| | | | A Control | B Water Immersion 2 Weeks | C Boiling Water 2 Hrs. | D Boiling Water 24 Hrs. |
| A8912-2 | Dorlux, clear EVA | None | (b) 24 | 7.9 | 1.6 | 2.5 |
| A8912-3 | Dorlux, white EVA | None | 12.3 | 4.8 | 1.4 | 2.6 |
| A8912-4 | Dorlux sanded, white EVA | None | 11.9 | 12.3 | 3.1 | 0 |
| A8912-5 | Dorlux, white EVA | SS4179 | (b) 24 | variable 0 - 13 | 1.5 | 2.7 |
| A8912-6 | Dorlux, white EVA | A8330B | (b) 23.5 | 7.9 | 1.6 | 1.7 |
| A8912-7 | Dorlux, vac. dried, white EVA | None | 4.02 | - | - | - |
| A8913-1 | Glass A, clear EVA | None | 1.84 | - | - | - |
| A8913-6 | Glass B, clear EVA | None | 4.51 | - | - | - |
| A8913-2 | Glass A, clear EVA | SS4179 | (b) 21.5 | 5.6 | 2.2 | 13.8 |
| A8913-3 | Glass B, clear EVA | SS4179 | (b) 18.5 | 5.7 | 2.5 | (b) Broken |
| A8913-4 | Glass A, clear EVA | A8330B | (b) 21.9 | (b) 23.5 | (b) 30.0 | (b) 17.5 |
| A8913-5 | Glass B, clear EVA | A8330B | (b) 20.8 | (b) 27.9 | (b) 25 | 9.6 |
| A8928-1 | Korad 201R, clear EVA | None | 2.3 | variable 1 - 17 | variable 1 - 16 | variable 1 - 14 |
| A8928-2 | Tedlar UT, clear EVA | None | 13.2 | variable 0 - 29 | 10 | 10 |
| A8928-3 | Aluminum foil, clear EVA | Z6030W | (a) | - | - | - |
| | Copper foil, clear EVA | A8921-1 | (a) | - | - | - |
| | Aluminum foil, clear EVA | None | (a) | 0 | - | - |
| A8930 B | Dorlux, wht. EVA + SS4179 | Internal | 10.5 | 8.1 | 2.2 | 2.5 |
| A8930 A | Dorlux, wht. EVA + A8921-2 | Internal | 17.7 | 14.6 | 3.5 | 2.9 |
| A8929-D2 | Glass, clr. EVA + SS4179 | Internal | Appx. 30 | variable 4 - 20 | (b) 25 | (b) 9.7 |
| A8929-C2 | Glass, clr. EVA + A8921-2 | Internal | (b) 23 | (b) 21 | (b) 30 | (b) 11 |
| A8929-D1 | Glass, clr. EVA + SS4179 | Internal | 9.9 | 3.5 | 2.3 | 2.2 |
| A8929-C1 | Glass, clr. EVA + A8921-2 | Internal | (b) 32 | (b) 24 | 10 | 10.5 |

(a) Delaminated, no strength. (b) Cohesive failure in polymer.

TABLE 5
PRIMER FORMULATIONS

- a. SS-4179 Proprietary formulation, General Electric Co.

- *b. A8921-2 A mixture of Dow Corning silane primers;
 - Z6030 silane.....9 parts
 - Z6020 silane.....1 part

- c. A8330 B Hydrolyzed Dow Corning Z-6030 primer;
 - Z-6030.....49.8%
 - Methanol.....39.8%
 - Water.....9.9%
 - Acetic acid.....0.39%

Mix and heat to reflex for one hour or permit to
stand at room temperature for 24 hours before using.

*Should be used within one month period of time after mixing and kept under refrigeration when not in use.

TABLE 6

Two-Cell Experimental Modules - Exposure Studies

| System Number | Specimen Number | Substrate | Pottant | Cover | Exposure | | (a) I_{sc} (%) | Condition Upon Exposure |
|---------------|-----------------|-----------|----------|-------|-----------|---------------|------------------------|---|
| | | | | | Condition | Time (Months) | | |
| 5 | 4880-2 | Polyester | RTV-615 | Halar | EMMAQUA | 4 | 106 | Excellent; browning of substrate, mild corrosion of interconnect; slight haze on cover. |
| 5 | 4880-1 | Polyester | RTV-615 | Halar | EMMAQUA | 8 | 100 | Excellent; same as above, but slight increase in browning of substrate. |
| 5 | 4880-3 | Polyester | RTV-615 | Halar | We-Om | 4 | 90.1 | Excellent; light yellowing of substrate; haze on cover of deposit. |
| 5 | 4885-1 | Polyester | RTV-615 | Halar | We-Om | 8 | 97.9 | Identical with 4 months except for more corrosion of interconnect. |
| 5 | 4884-1 | Polyester | RTV-615 | Halar | RS-4 | 4 | 109 | Excellent; light yellowing of substrate. |
| 5 | 4884-2 | Polyester | RTV-615 | Halar | RS-4 | 8 | 99.4 | Excellent; dark yellowing of substrate; some corrosion of middle interconnect |
| 6 | 4889-1 | Polyester | Syl. 184 | PFA | EMMAQUA | 4 | 98 | Good; browning of substrate; delamination of silicone near one cell; no corrosion. |

(a) I_{sc} - short-circuit current, % remaining after exposure

...Continued

TABLE 6 (Continued - 2)

| System Number | Specimen Number | Substrate | Pottant | Cover | Exposure | | I _{sc} (%) | Condition Upon Exposure |
|---------------|-----------------|-----------|----------|--------|-----------|---------------|---------------------|---|
| | | | | | Condition | Time (Months) | | |
| 6 | 4889-2 | Polyester | Syl. 184 | PFA | EMMAQUA | 8 | 96.4 | Excellent; browning of substrate; delamination of cover at one corner; slight corrosion visible. |
| 6 | 4888-2 | Polyester | Syl. 184 | PFA | We-Om | 4 | 110 | Good; slight yellowing of substrate; slight delamination of cover; possible delamination of pottant. Haze on cover. |
| 6 | 4885-A | Polyester | Syl. 184 | PFA | We-Om | 8 | 101 | Good; light yellow substrate. Slight delamination of cover. |
| 6 | 4888-3 | Polyester | Syl. 184 | PFA | RS-4 | 4 | 115 | Excellent; light yellow color; slight corrosion. |
| 6 | 4888-1 | Polyester | Syl. 184 | PFA | RS-4 | 8 | 98.3 | Excellent; very light brown color. No corrosion. |
| 7 | 6686-3 | Polyester | Viton | DR-61K | We-Om | 4 | - | Destroyed. Cover delamination; corrosion of middle interconnect; browning of pottant over cells; deposit on cover. |
| 7 | 6686-4 | Polyester | Viton | DR-61K | We-Om | 8 | - | Destroyed. Cover warping and delamination; browning of pottant; hazy deposit on cover. |

...Continued

TABLE 6 (Continued - 3)

| System Number | Specimen Number | Substrate | Pottant | Cover | Exposure | | I _{sc} (%) | Condition Upon Exposure |
|---------------|-----------------|-----------|---------|--------|-----------|---------------|---------------------|---|
| | | | | | Condition | Time (Months) | | |
| 7 | 6685-1 | Polyester | Viton | DR-61K | RS-4 | 4 | 90.6 | Destroyed. Delamination of cover; yellowing of substrate; browning of pottant. |
| 7 | 6680-1 | Polyester | Viton | DR-61K | RS-4 | 8 | - | Poor. Dark brown pottant; some delamination of cover; bubbles in pottant. |
| 8 | 4898-16 | Polyester | Q3-6527 | V-811 | EMMAQUA | 4 | 94.2 | Fair; light browning of substrate; very slight delamination. Many large bubbles over cells. |
| 8 | 4898-14 | Polyester | Q3-6527 | V-811 | EMMAQUA | 8 | 97.7 | Fair; light brown substrate; some bubbles in pottant; very slight edge delamination. |
| 8 | 4898-15 | Polyester | Q3-6527 | V-811 | We-Om | 4 | 108 | Fair; hazy deposit on cover; light yellow substrate; few bubbles in pottant. |
| 8 | 4898-10 | Polyester | Q3-6527 | V-811 | We-Om | 8 | 95.4 | Fair; hazy deposit on cover; light yellow substrate; very few bubbles. |
| 8 | 4898-13 | Polyester | Q3-6527 | V-811 | RS-4 | 4 | 90.5 | Good; light yellow; a few small bubbles. |
| 8 | 4894-1 | Polyester | Q3-6527 | V-811 | RS-4 | 8 | 84.1 | Fair; strong yellow of pottant and substrate; few small bubbles. |

...Continued

TABLE 6 (Continued - 4)

| System Number | Specimen Number | Substrate | Pottant | Cover | Exposure | | I _{sc} (%) | Condition Upon Exposure |
|---------------|-----------------|-----------|----------|--------|-----------|---------------|---------------------|---|
| | | | | | Condition | Time (Months) | | |
| 12 | 4898-3 | Aluminum | Q3-6527 | Glass | EMMAQUA | 4 | 101 | Poor; glass cracked; bubbles in pottant. |
| 12 | 4898-2 | Aluminum | Q3-6527 | Glass | EMMAQUA | 8 | 0 Short | Good; slight deposit on glass. Bubbles in pottant. |
| 12 | 4898-9 | Aluminum | Q3-6527 | Glass | We-Om | 4 | 95.3 | Good; some deposit on glass; some bubbles in pottant. |
| 12 | 4898-1 | Aluminum | Q3-6527 | Glass | We-Om | 8 | 99.2 | Good; some deposit on glass; some bubbles in pottant. |
| 12 | 4898-6 | Aluminum | Q3-6527 | Glass | RS-4 | 4 | 101 | Poor; fractured cell; some bubbles in pottant. |
| 12 | 4898-8 | Aluminum | Q3-6527 | Glass | RS-4 | 8 | 95.8 | Poor; fractured cell; some bubbles in pottant. |
| 13 | 4873-6 | NEMA | Syl. 184 | Tedlar | EMMAQUA | 4 | 100 | Fair; dark brown substrate; edge delamination of cover. |
| 13 | 4873- | NEMA | Syl. 184 | Tedlar | EMMAQUA | 8 | 97.6 | Fair; dark brown substrate; edge delamination of cover. |
| 13 | 4874-1 | NEMA | Syl. 184 | Tedlar | We-Om | 4 | 96.2 | Poor; light brown color; deposit on cover; cover cracked. |

...Continued

T-10

C-2

TABLE 6 (Continued - 5)

| System Number | Specimen Number | Substrate | Pottant | Cover | Exposure | | I _{sc} (%) | Condition Upon Exposure |
|---------------|-----------------|-----------|----------|--------|-----------|---------------|---------------------|---|
| | | | | | Condition | Time (Months) | | |
| 13 | 4874-4 | NEMA | Syl. 184 | Tedlar | We-Om | 8 | 100 | Poor; light brown color; cover cracked and peeling off. |
| 13 | 4873-5 | NEMA | Syl. 184 | Tedlar | RS-4 | 4 | 99.4 | Poor; light brown color; cover cracked and brittle. |
| 13 | 4874-3 | NEMA | Syl. 184 | Tedlar | RS-4 | 8 | 82.5 | Poor; dark brown; cover severely cracked and peeling off. |

TABLE 7

TENSILE SPECIMEN EXPOSURE

Phoenix, Fixed Angle, 45° South

Time: 12 Months

| Resin | Optical Transmission (%) | | | | Mechanical Properties | | | | | | | | Remarks |
|------------------|--------------------------|------|---------|------|-----------------------|------|----------------------------------|-------------|----------------|------|--------------------|--------|-------------------|
| | UV | | Visible | | Yield Str. (psi) | | Modulus (psi x 10 ⁵) | | Elongation (%) | | Tensile Str. (psi) | | |
| | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | |
| Halar 500 | 36 | 30 | 81 | 66 | 5030 | 4586 | 2.23 | 1.01 | 175 | 167 | 6090 | 5321 | (a) |
| Tedlar 400SG20TR | 13 | 14 | 76 | 49 | (b) 5020 | 5625 | 3.60 | 1.30 | 120 | 135 | 12,100 | 10,127 | (a) |
| Plexi DR-61K | 0 | 1 | 90 | 77 | 5630 | 5413 | 2.20 | 1.44 | 17 | 11 | 5380 | 5101 | (a) |
| FEP-100 | 34 | 33 | 84 | 79 | (b) 2130 | 1840 | 0.704 | 0.57 | 220 | 265 | 2800 | 2810 | (a) |
| Tenite 479 | 44 | (c) | 92 | (c) | 3470 | (c) | 1.54 | (c) | 81 | (c) | 4400 | (c) | Disintegrated |
| Sylgard 184 | 32 | 22 | 76 | 57 | NY | NY | (e) 586 | (e) 1820 | 106 | 109 | 930 | 1016 | Dirt accumulation |
| Kel-F 6060 | 24 | 47 | 82 | 87 | 5690 | 4667 | 1.72 | 1.14 | 130 | 114 | 5680 | 4533 | (a) |
| Lexan 123 | 0 | 0 | 88 | 82 | 8500 | 8204 | 3.14 | 1.88 | 104 | 18 | 8160 | 6772 | Yellow; hazy |
| Plexi V-811 | 75 | 65 | 92 | 86 | 9030 | NY | 4.18 | 2.56 | 5 | 5 | 9030 | 6776 | (a) |
| Saflex PT, PVB | - | (d) | 90 | (d) | 830 | (d) | 0.051 | (d) | 180 | (d) | 4010 | (d) | Severely flowed |

Code: Cont. = Control
 Exp. = Exposed
 Str. = Strength
 NY = No Yield

(a) No visual change
 (b) Pseudo yield point
 (c) Broken

(d) Material flowed
 (e) Modulus at 100 percent, psi x 1

TABLE 8

TENSILE SPECIMEN EXPOSURE

EMMAQUA - Desert Sunshine Exposure Tests, Inc.

Time: 12 Months

| Resin | Optical Transmission (%) | | | | Mechanical Properties | | | | | | | | Remarks |
|------------------|--------------------------|------|---------|------|-----------------------|------|----------------------------------|------|----------------|------|--------------------|------|-----------------|
| | UV | | Visible | | Yield Str. (psi) | | Modulus (psi x 10 ⁵) | | Elongation (%) | | Tensile Str. (psi) | | |
| | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | |
| Halar 500 | 36 | 9 | 81 | 58 | 5030 | 4622 | 2.23 | 1.26 | 175 | 138 | 6090 | 5178 | (a) |
| Tedlar 400SG20TR | 13 | 1 | 76 | 28 | (b) 5820 | 5938 | 3.60 | 1.46 | 120 | 116 | 12,100 | 9635 | (a) |
| Plexi DR-61K | 0 | 2 | 90 | 70 | 5630 | NY | 2.20 | 1.44 | 17 | 7 | 5380 | 5363 | (a) |
| FEP-100 | 34 | 15 | 84 | 55 | (b) 2130 | 1896 | 0.704 | 0.37 | 220 | 292 | 2800 | 3368 | (a) |
| Tenite 479 | 44 | (c) | 92 | (c) | 3470 | (c) | 1.54 | (c) | 81 | (c) | 4400 | (c) | Disintegrated |
| Sylgard 184 | 32 | 0 | 76 | 4 | NY | (c) | (e) 586 | (c) | 106 | (c) | 930 | (c) | Broken off |
| Kel-F 6060 | 24 | 27 | 82 | 72 | 5690 | 5127 | 1.72 | 1.20 | 130 | 79 | 5680 | 4976 | (a) |
| Lexan 123 | 0 | 0 | 88 | 48 | 8500 | 7955 | 3.14 | 1.87 | 104 | 10 | 8160 | 6938 | Hazy; yellowish |
| Plexi V-811 | 75 | 26 | 92 | 71 | 9030 | NY | 4.18 | 2.26 | 5 | 1.5 | 9030 | 4348 | Brittle |
| Saflex PT, PVB | - | (d) | 90 | (d) | 830 | (d) | 0.051 | (d) | 180 | (d) | 4010 | (d) | Severe flow |

Code: Cont. = Control
 Exp. = Exposed
 Str. = Strength
 NY = No Yield

(a) No visual change
 (b) Pseudo yield point
 (c) Broken

(d) Material flowed
 (e) Modulus at 100 percent, psi x 1

TABLE 9
TENSILE SPECIMEN EXPOSURE
Florida, Fixed Angle, 45° South
Time: 12 Months

| Resin | Optical Transmission (%) | | | | Mechanical Properties | | | | | | | | Remarks |
|------------------|--------------------------|------|---------|------|-----------------------|------|----------------------------------|------|----------------|------|--------------------|--------|-------------------|
| | UV | | Visible | | Yield Str. (psi) | | Modulus (psi x 10 ⁵) | | Elongation (%) | | Tensile Str. (psi) | | |
| | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | Cont. | Exp. | |
| Halar 500 | 36 | 26 | 81 | 78 | 5030 | 4628 | 2.23 | 0.84 | 175 | 202 | 6090 | 6077 | (a) |
| Tedlar 400SG20TR | 13 | 12 | 76 | 62 | (b) 5820 | 5647 | 3.60 | 1.18 | 120 | 147 | 12,100 | 10,567 | (a) |
| Plexi DR-61K | 0 | 2 | 90 | 80 | 5630 | 5538 | 2.20 | 1.62 | 17 | 8 | 5380 | 5390 | (a) |
| FEP-100 | 34 | 35 | 84 | 82 | (b) 2130 | 1915 | 0.704 | 0.41 | 220 | 329 | 2800 | 3422 | (a) |
| Tenite 479 | 44 | (c) | 92 | (c) | 3470 | (c) | 1.54 | (c) | 81 | (c) | 4400 | (c) | Disintegrated |
| Sylgard 184 | 32 | 32 | 76 | 65 | NY | NY | (e) 586 | 1380 | 106 | 112 | 930 | 766 | Dirt accumulation |
| Kel-F 6060 | 24 | 40 | 82 | 79 | 5700 | 4876 | 1.72 | 1.22 | 130 | 131 | 5680 | 5028 | (a) |
| Lexan 123 | 0 | 0 | 88 | 78 | 8500 | 8565 | 3.14 | 1.98 | 104 | 12 | 8160 | 6862 | Hazy, yellow |
| Plexi V-811 | 75 | 74 | 92 | 89 | 9030 | NY | 4.18 | 2.89 | 5 | 5 | 9030 | 6840 | (a) |
| Saflex PT, PVB | - | (d) | 90 | (d) | 830 | (d) | 0.051 | (d) | 180 | (d) | 4010 | (d) | Severely flowed |

Code: Cont. = Control
Exp. = Exposed
Str. = Strength
NY = No Yield

(a) No visual change
(b) Pseudo yield point
(c) Broken

(d) Material flowed
(e) Modulus at 100 percent, psi x i

TABLE 10

TENSILE SPECIMEN EXPOSURE
Percent Tensile Strength Retained
After Exposure

| Material | Unaged Control (psi) | Weather- Ometer 8 Months | Phoenix 12 Months | EMMAQUA | |
|------------------|----------------------------|-----------------------------------|-------------------------|-------------|--------------|
| | | | | 4 Months | 12 Months |
| FEP 100 | 2800 | 96 | 100 | 116 | 120 |
| Halar 500 | 6090 | 113 | 87 | 87 | 85 |
| Kel-F 6060 | 5680 | 96 | 80 | 68 | 88 |
| Tedlar 400SG20TR | 12,100 | 84 | 84 | 86 | 80 |
| Plexiglas DR61K | 5380 | 60 | 93 | 107 | 99 |
| Plexiglas V811 | 9030 | 80 | 75 | 61 | 48 |
| Sylgard 184 | 930 | 50 | 109 | 57 | (b) |
| Tenite 479 | 4400 | (a) | (a) | 18 | (a) |
| Lexan 123 | 8160 | NT | 83 | 82 | 85 |
| Saflex PT | 4010 | (c) | (c) | (c) | (c) |

(a) Disintegrated

NT = Not Tested

(b) Missing from test site

(c) Severely flowed

TABLE 11

TENSILE SPECIMEN EXPOSURE
Percent Elongation Retained

| Material | Unaged Control Elongation (%) | 240 Days | | EMMAQUA | |
|------------------|--|--------------------|-----------------|-------------|--------------------|
| | | Weather- Ometer | RS-4 Sunlamp | 4 Months | 12 Months |
| FEP 100 | 220 | 142 | 120 | 120 | 133 |
| Halar 500 | 175 | 145 | 133 | 104 | 79 |
| Kel-F 6060 | 130 | 127 | 118 | 54 | 61 |
| Tedlar 400SG20TR | 120 | 143 | 74 | 121 | 97 |
| Plexiglas DR61K | 17 | 23 | 6 | 76 | 41 |
| Plexiglas V811 | 5 | 60 | 30 | 40 | 30 |
| Sylgard 184 | 106 | 83 | 82 | 133 | 102 ^(b) |
| Tenite 479 | 81 | (a) | (a) | (a) | (a) |
| Lexan 123 | 104 | (a) | (a) | 7 | 10 |

(a) Disintegrated

(b) Eight-month data

TABLE 12
TENSILE SPECIMEN EXPOSURE
Percent Transmission Retained
After Exposure Period

| Material | Original Trans- mission (%) | Weather- Ometer 8 Months | EMMAQUA | |
|------------------|--------------------------------------|-----------------------------------|-------------|--------------|
| | | | 4 Months | 12 Months |
| FEP 100 | 84 | 66 | 77 | 65 |
| Halar 500 | 81 | 58 | 76 | 71 |
| Kel-F 6060 | 82 | 56 | 69 | 88 |
| Tedlar 400SG20TR | 76 | 23 | 25 | 37 |
| Plexiglas DR61K | 90 | 70 | 83 | 78 |
| Plexiglas V811 | 92 | 75 | 86 | 77 |
| Sylgard 184 | 76 | 20 | 39 | 5 |
| Tenite 479 | 92 | (a) | (a) | (a) |
| Lexan 123 | 88 | 33 | 73 | 54 |

(a) Disintegrated

TABLE 13
CORROSION MONITORING

| Test Specimens | | | Salt Spray Corrosion Conditions | | | | | |
|----------------|------------------------------|-----------|---------------------------------|------------|------------|------------|------------|-------------|
| Notebook No. | Materials | Primer | 24 Hrs | 120 Hrs | 300 Hrs | 450 Hrs | 700 Hrs | 1600 Hrs |
| A8919-3 | Aluminum in EVA, tab exposed | None | 1 | 1 | 4,8 | 4,8 | 4,8 | 5,8 |
| A8919-4 | Galvanized steel in EVA | None | 1 | 1 | 1 | 1 | 3 | 5,8 |
| A8919-4 | Galvanized, EVA, tab exposed | None | 5 | 5 | 6,8 | 6,8 | 6,8 | 6,8 |
| A8919-6 | Mild steel in EVA | None | 1 | 1 | 1 | 2 | 5,8 | 5,8 |
| A8919-7 | Mild steel, EVA, tab exposed | None | 5 | 6 | 6,8 | 6,8 | 6,8 | 6,8 |
| A8919-8 | Galvanized steel, EVA | A8921-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A8919-9 | Mild Steel, EVA | A8921-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Mild Steel - Control | Uncoated | 4 | 6 | 6 | 6 | 6 | 6 |
| | Copper Control | Uncoated | 4 | 6 | 6 | 6 | 6 | 6 |
| | Aluminum Control | Uncoated | 1 | 5 | 6 | 6 | 6 | 6 |
| | Galvanized Control | Uncoated | 4 | 6 | 6 | 6 | 6 | 6 |
| | Unprotected Cell-Control | Uncoated | 1 | 4 | 5 | 6 | 6 | 6 |
| A8919-1 | Aluminum in EVA | None | 1 | 1 | 1 | 1 | 1 | 1 |
| A8922-1 | Copper in EVA | None | 1 | 1 | 1 | 1 | 1 | 1 |
| A8919-2 | Aluminum in EVA | A8921-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A8922-3 | Copper in EVA | A8921-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A8923-1 | Solar Cell in EVA | None | 1 | 1 | 1 | 1 | 1 | 1 |
| A8923-2 | Solar Cell in EVA | A8921-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A8923-3 | Solar Cell in EVA | GE SS4179 | 1 | 1 | 1 | 1 | 1 | 1 |
| A8920-1+2 | Galvanic Cell, Copper-Zinc | None | 1 | 1 | 1,9 | 1,9 | 3,9 | 3,9 |
| A8921-2 | Galvanic Cell, Copper-Zinc | A8921-1 | 1 | 1 | 1,9 | 1,9 | 3,9 | 3,9 |
| A8921-3 | Galvanic Cell, Cu-Zn,Wh.EVA | None | 1 | 1 | 1,9 | 1,9 | 3,9 | 3,9 |
| A8921-4 | Galvanic Cell, Cu-Zn,Wh.EVA | A8921-1 | 1 | 1 | 1,9 | 1,9 | 3,9 | 3,9 |
| A8922-4 | Copper in EVA, tab exposed | None | 1 | 1 | 5,8 | 5,8 | 5,8 | 5,8 |

- | | |
|---|--|
| 1. Unaffected | 6. Heavy corrosion visible (over 20% surface). |
| 2. Slight dulling of surface. | 7. Discoloration of polymer. |
| 3. Noticable dulling of surface. | 8. Delamination at interface. |
| 4. Light corrosion visible. | 9. No measurable current. |
| 5. Medium corrosion visible (10% of surface). | |

SCRIM MATERIAL SURVEY

| Manufacturer | Product Code | Material | Cell Size (Mils x Mils) | Weight (9/Yd ²) | Scrim Thickness (Mil) | Cell Type | Cost (\$/Yd ²) | Cost \$/ft ² |
|--------------------------|--------------|--------------|-------------------------|-----------------------------|-----------------------|-----------|----------------------------|-------------------------|
| Burlington Glass Fabrics | 191 | Glass Fibers | 50 x 100 | 46.8 | 5 | .8Q | \$.34 | \$.038 |
| | 1562 | Glass Fibers | 33 x 63 | 51.1 | 4.5 | 8Q | \$.24 | \$.027 |
| | 1620 | Glass Fibers | 50 x 50 | 45.5 | 4 | 8Q | \$.15 | \$.017 |
| | 1621 | Glass Fibers | 33 x 71 | 67.0 | 6.2 | 8Q | \$.23 | \$.025 |
| | 1658 | Glass Fibers | 50 x 100 | 51.1 | 4 | 8Q | \$.12 | \$.013 |
| | 1659 | Glass Fibers | 50 x 100 | 46.5 | 4.7 | 8Q | \$.13 | \$.014 |
| Bay Mills (Bayer) | Qx2111/P-14 | Polyester | 500 x 1000 | 15.3 | ~10 | 8Q | \$.05 | \$.005 |
| | Qx8410/P-14 | Polyester | 125 x 125 | 65.3 | ~10 | 8Q | \$.20 | \$.022 |
| | GCD1120/A | Polyester | 2000 x 1000 | 5.1 | ~6 | 8Q | \$.032 | \$.003 |
| Apex Mills Corp. | Alto | Nylon | 50 x 50 | 9.8 | ~5 | Rhombic | \$.25 | \$.028 |
| | Duralon 30 | Nylon | 125 x 125 | 40.7 | ~12 | Rhombic | \$.38 | \$.042 |
| | Duralon S50 | Nylon | 63 x 63 | 34.3 | ~8 | SQ | \$.37 | \$.041 |
| | D1 | Nylon | 438 x 438 | 39.9 | ~14 | Hexagonal | \$.42 | \$.047 |
| | 727 | Nylon | 34 x 34 | 15.1 | ~5 | Rhombic | \$.36 | \$.04 |

TABLE 14

TABLE 15

POLYESTER SEPARATOR MATERIALS

ELECTRICAL INSULATION GRADES
POLYESTER

| Style | 6600 | 6800 | 6100 | 7200 |
|--|-----------|-----------|-----------|---------------|
| Fiber | Polyester | Polyester | Polyester | Polyester |
| Fiber Orientation | Random | Random | Random | Undirectional |
| Weight (g/m ²) | 60 | 80 | 100 | 22 |
| Average thickness (.001") | 4.0 | 4.5 | 5.0 | 1.2 |
| Tensile strength (lbs/2") MD | 18 | 20 | 22 | 16 |
| AMD | 49 | 51 | 54 | 1 |
| Elongation (%) MD | 13 | 21 | 28 | 18 |
| AMD | 34 | 26 | 26 | 1 |
| Price \$/ft ² non-a. volume! | \$0.053 | \$0.063 | \$0.073 | \$0.019 |

a. No volume price reductions offered with this product.

TABLE 16

NON-WOVEN GLASS SEPARATOR MATERIALS

Supplied by:

Crane and Co., Dalton, Mass.^{a.}

"Craneglass 230"

| <u>Properties</u> | <u>Thickness-Inches*</u> | | | | |
|--|--------------------------|-------------|-------------|-------------|-------------|
| | <u>.003</u> | <u>.005</u> | <u>.007</u> | <u>.009</u> | <u>.012</u> |
| Substance Weight-Lbs. (17" x 22" - 500) | 3.5 | 6.1 | 7.8 | 11.2 | 15.2 |
| Grams/Square Meter | 13.2 | 22.9 | 29.3 | 42.1 | 57.1 |
| Density (grams/cm ³) | 0.17 | 0.18 | 0.18 | 0.18 | 0.19 |
| Tensiles (Lbs/In.) | | | | | |
| M.D. | 2.8 | 5.9 | 8.7 | 13.8 | 17.7 |
| C.D. | 1.6 | 2.6 | 3.5 | 5.0 | 6.8 |
| Elongation (%) | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Tear (Elmendorf) | | | | | |
| M.D. (grams) | 23 | 35 | 43 | 72 | 84 |
| C.D. (grams) | 17 | 25 | 30 | 57 | 62 |
| Porosity (CFM/ft ² at .5" water) | 785 | 515 | 360 | 256 | 200 |
| Cost per pound \$/lb | 2.45 | 1.68 | 1.63 | 1.58 | 1.55 |
| Yd ² /lb | 41.3 | 23.7 | 18.5 | 12.9 | 9.5 |
| ft ² /lb | 317 | 213 | 166 | 116 | 85 |
| Cost ¢/ft ² | 0.66 | 0.78 | 0.97 | 1.36 | 1.81 |

a. Distributed by Electrolock, Inc., Chagrin Falls, Ohio

*Thickness is an approximate value to be used only as a guide.

TABLE 17

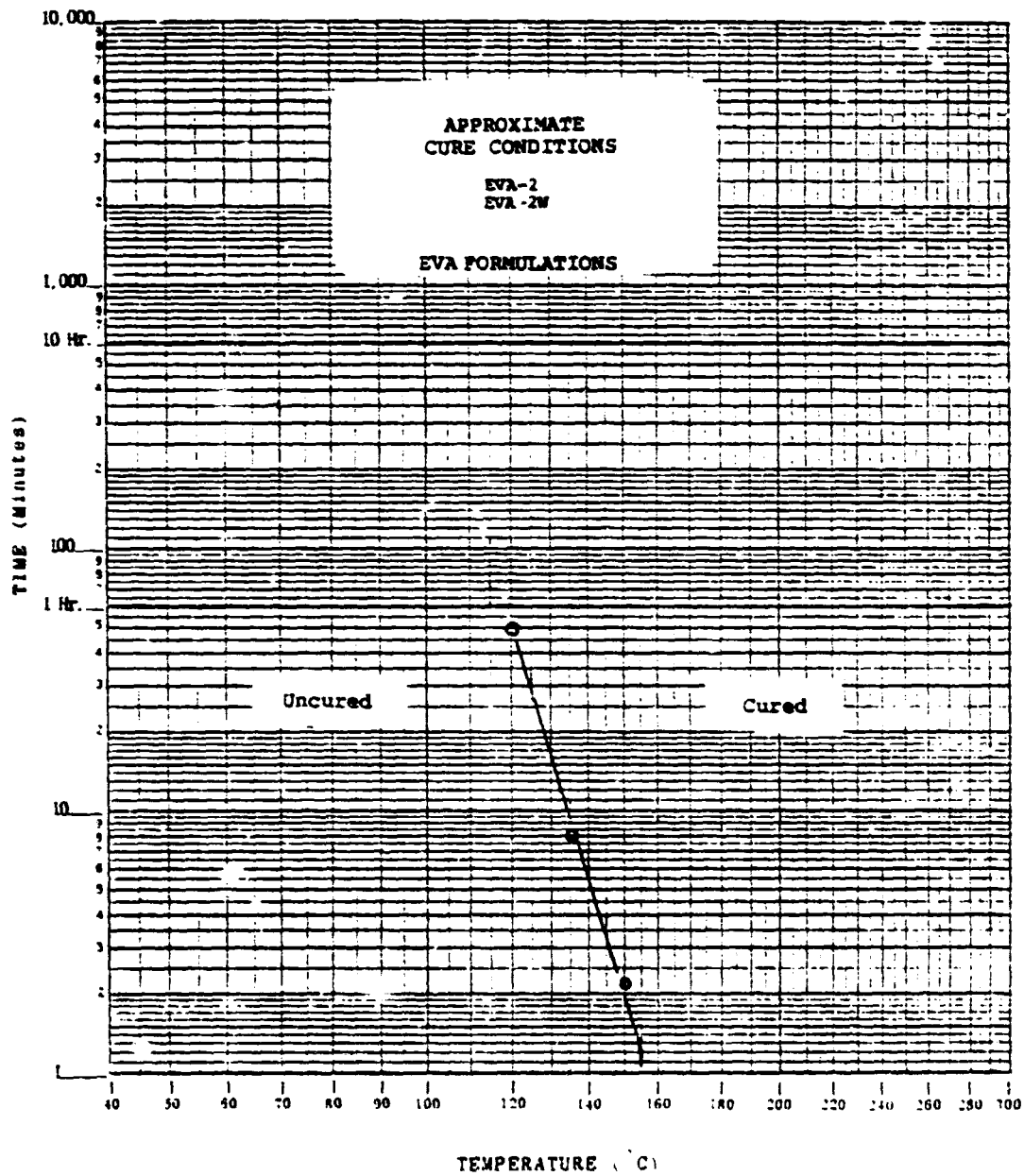
Cost and Construction Comparison - Sandwich Substrates
(4 Foot by 8 Foot Modules)
ALL PRICES IN 1978 DOLLARS

| Design Number | 1 | 2 | 3 | 4 | 5 |
|---|---------------------|---------|---------|-----------------|-----------------|
| . Sandwich | | | | | |
| Skin material | PVC | Steel | Steel | Steel | Steel |
| Skin thickness (inches) | 0.04 | 0.01 | 0.01 | 0.01 | 0.01 |
| Core material | PU Foam | PU Foam | PU Foam | Fir Slatting | Styrene Grid |
| Core thickness (inches) | 0.25 | 0.375 | 0.50 | 0.50 | 0.50 |
| Skin costs (\$) | 7.99 | 6.52 | 6.52 | 6.52 | 6.52 |
| Core costs (\$) | 1.64 | 1.89 | 1.89 | 2.50 | 3.38 |
| Adhesive costs (\$) | 4.03 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total cost, 4' x 8' (2.97 M ²) (\$) | 13.66 | 9.41 | 9.41 | 10.02 | 10.90 |
| Cost per ft ² (\$) | 0.43 | 0.29 | 0.29 | 0.31 | 0.34 |
| Cost per M ² (\$) | 4.59 | 3.17 | 3.17 | 3.37 | 3.67 |
| . Support and Foundation | | | | | |
| Woodwork, nails, etc. (\$) | 5.50 ^(a) | 6.60 | 5.50 | 5.50 | 4.99 |
| Foundation, concrete posts (\$) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Cost per M ² (\$) | 2.19 | 2.56 | 2.19 | 2.19 | 2.02 |
| . Substrate, Support, and Foundation | | | | | |
| Total cost per M ² (\$) | 6.78 | 5.73 | 5.34 | 5.57 | 5.69 |
| . Remaining Encapsulants^(b) | | | | | |
| Pottant cost per M ² (\$) | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 |
| Outer cover cost per M ² (\$) | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| Adhesive cost per M ² | 0.43 | 0.43 | 0.43 | 0.43 | 0.43 |
| Approximated Total Encapsulation Cost (\$/M ²) | 7.97 | 6.92 | 6.53 | 6.76 | 6.88 |

(a) Using support system from Design No. 3

(b) Prices from tentative cost allocations

FIGURE 1



(NOTE: Compositions do not cure below 120°C)

Figure 2
Vacuum Bag Assembly
(initial design)

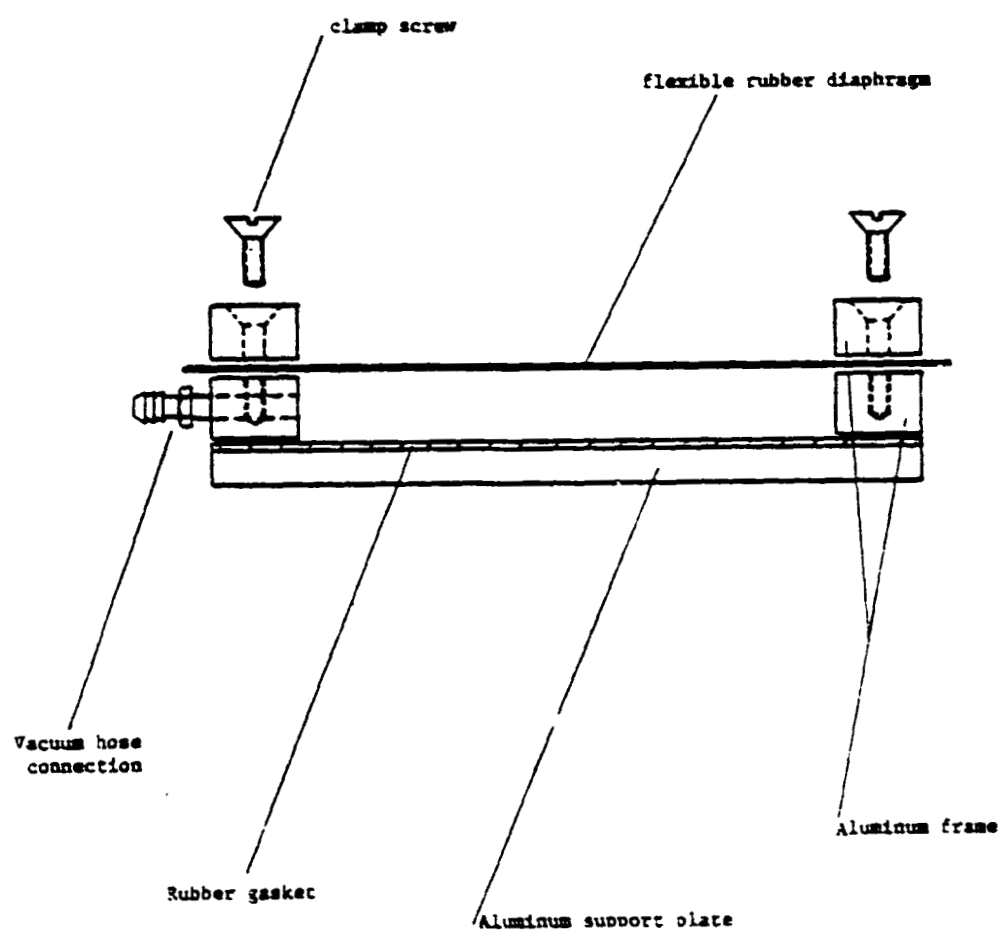
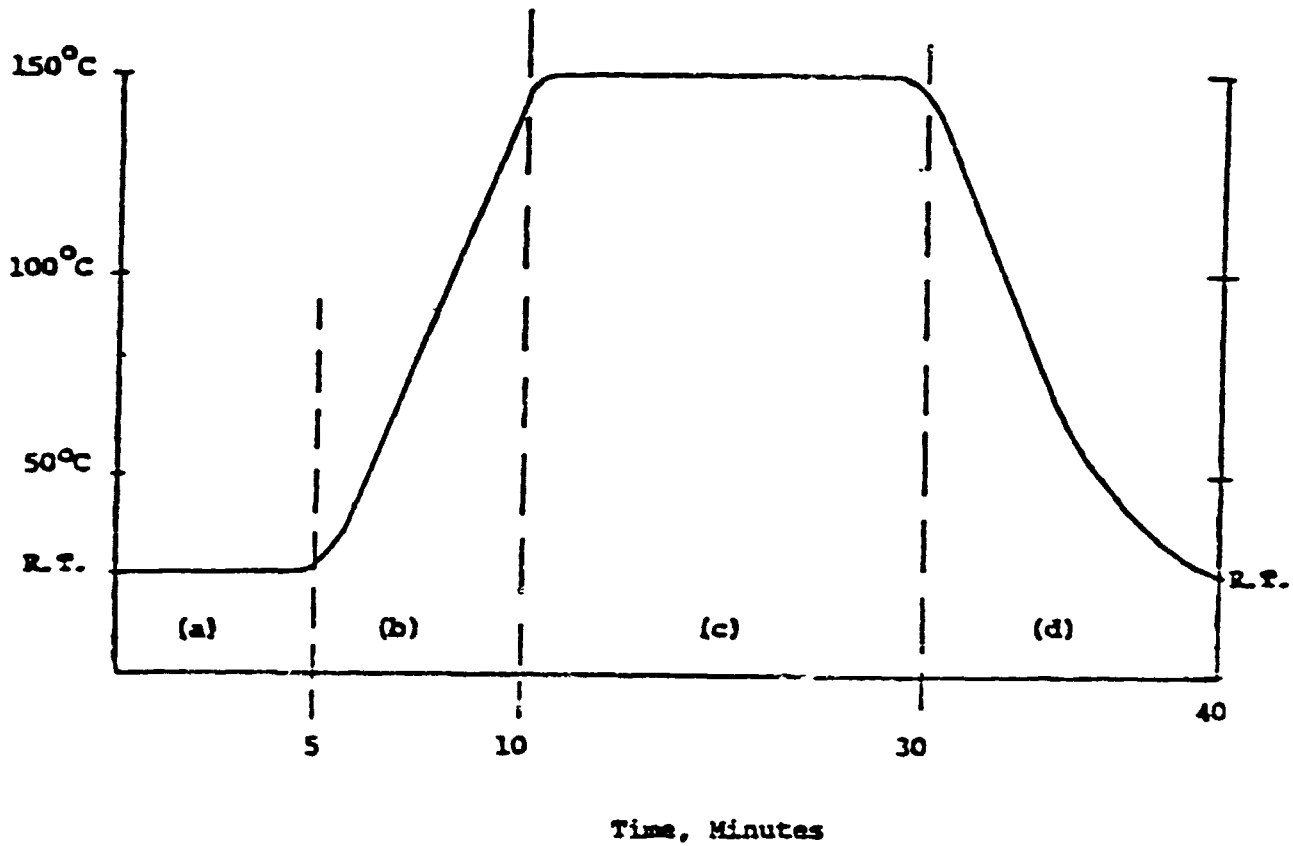


FIGURE 3

VACUUM BAG FABRICATION CYCLE

11"x15" Modules
A8346

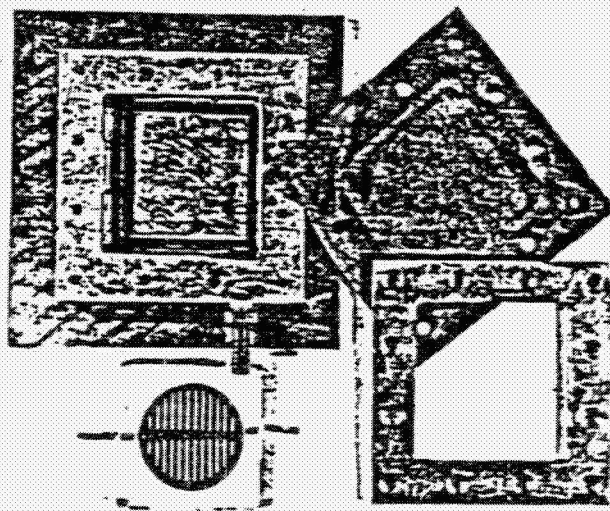


• Vacuum Applied Throughout Cycle, 30 in. Hg.

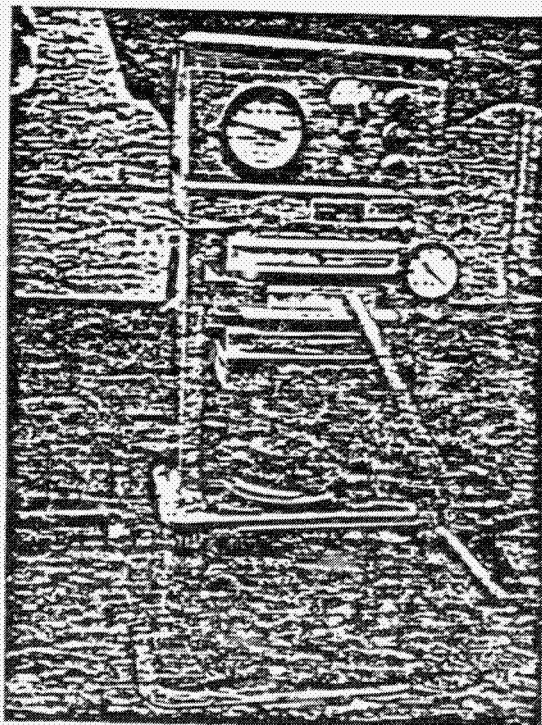
- (a) Room Temperature Evacuation
- (b) Onset of Heat Cycle
- (c) Fusion and Cure
- (d) Cooling

Figure 4

ONE-CELLED MODULE FABRICATION
(SPRINGBORN LABORATORIES)



VACUUM BAG ASSEMBLY



EVACUATION, FUSION,
AND CURE IN
HEATED PLATEN PRESS

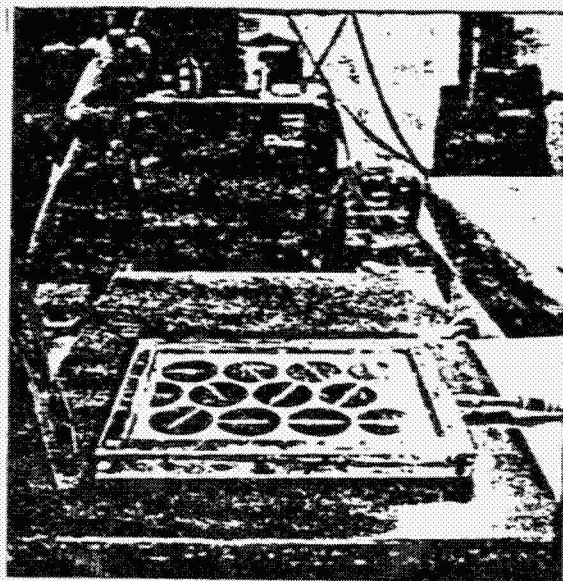


ENGINEERING DEPARTMENT
SPRINGBORN LABORATORIES

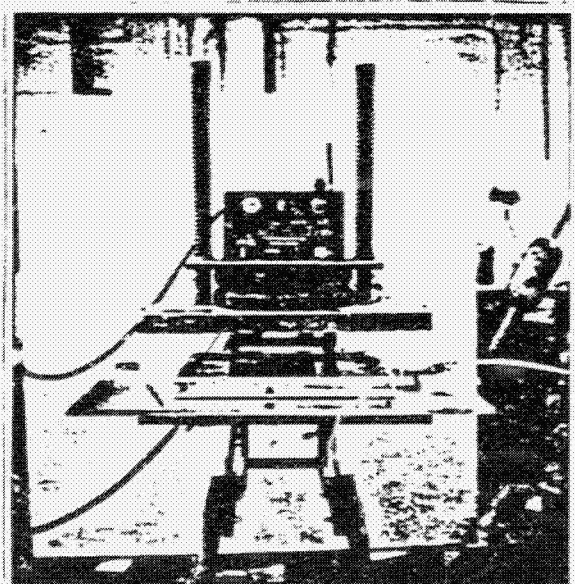
Figure 5

VACUUM BAG EQUIPMENT
AND MODULE FABRICATION

SOLAR POWER CORPORATION



VACUUM BAG AND MODULE

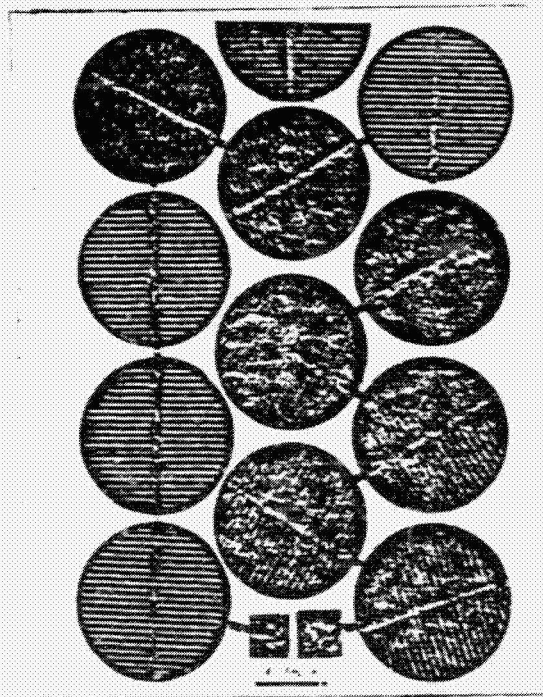


VACUUM BAG AND HEATED PRESS

Figure 6

COMPLETED
MINIMODULE

11" x 15"



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OF POOR QUALITY

FIGURE 7

EXPERIMENTAL DOUBLE VACUUM BAG ASSEMBLY

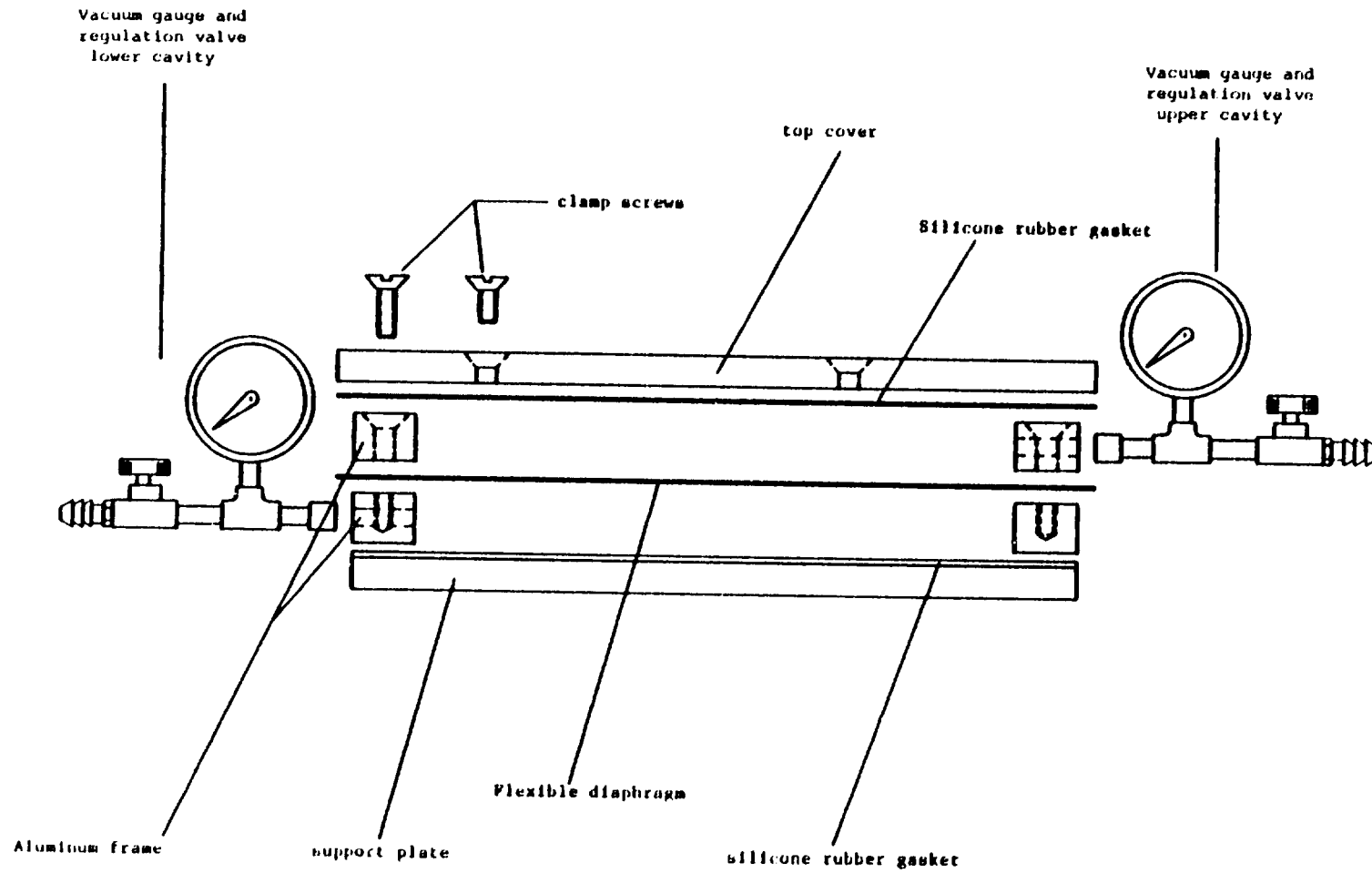
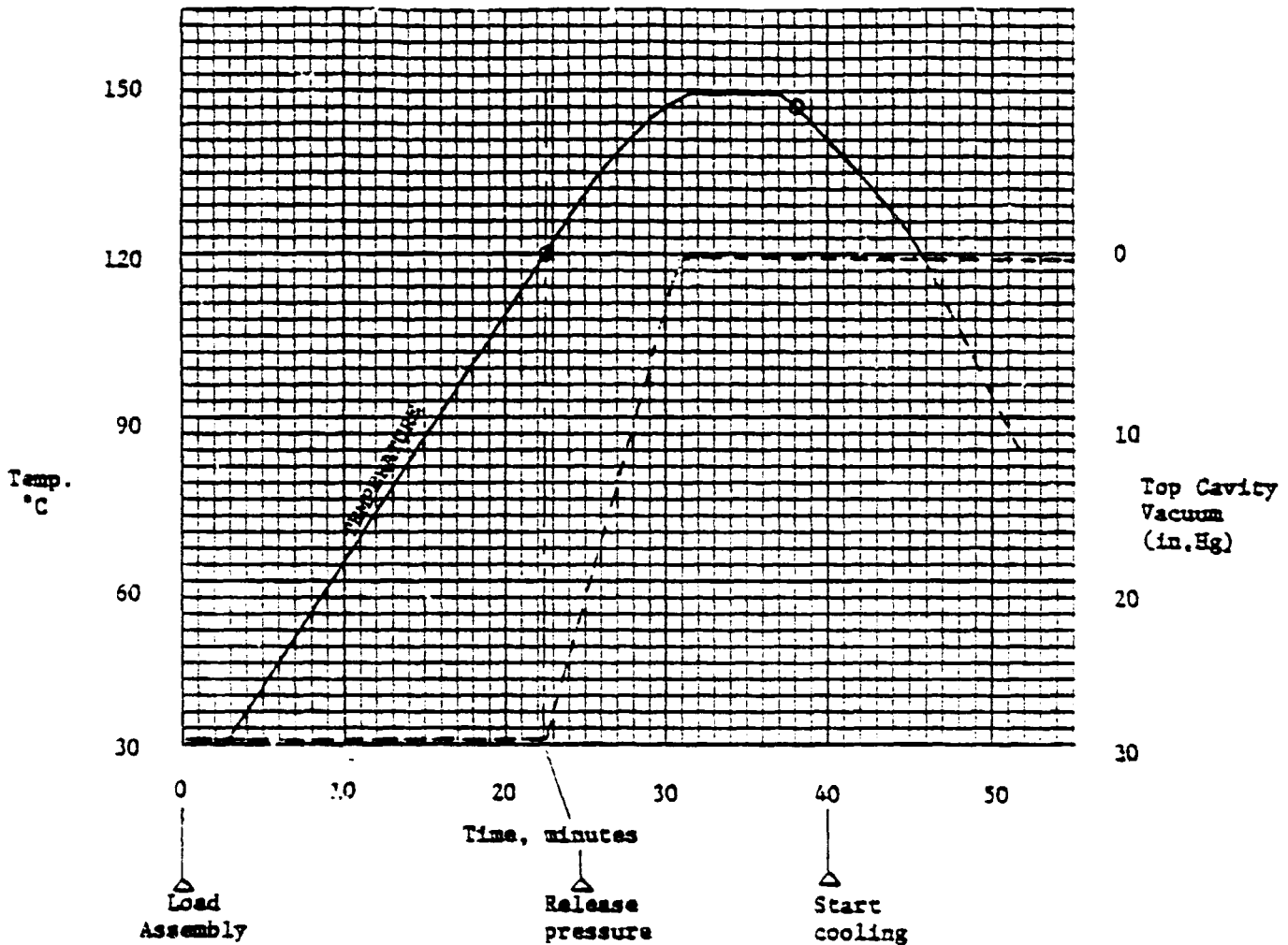


FIGURE 8
Time/Temperature/Pressure Cycle
Vacuum Bag Module Fabrication



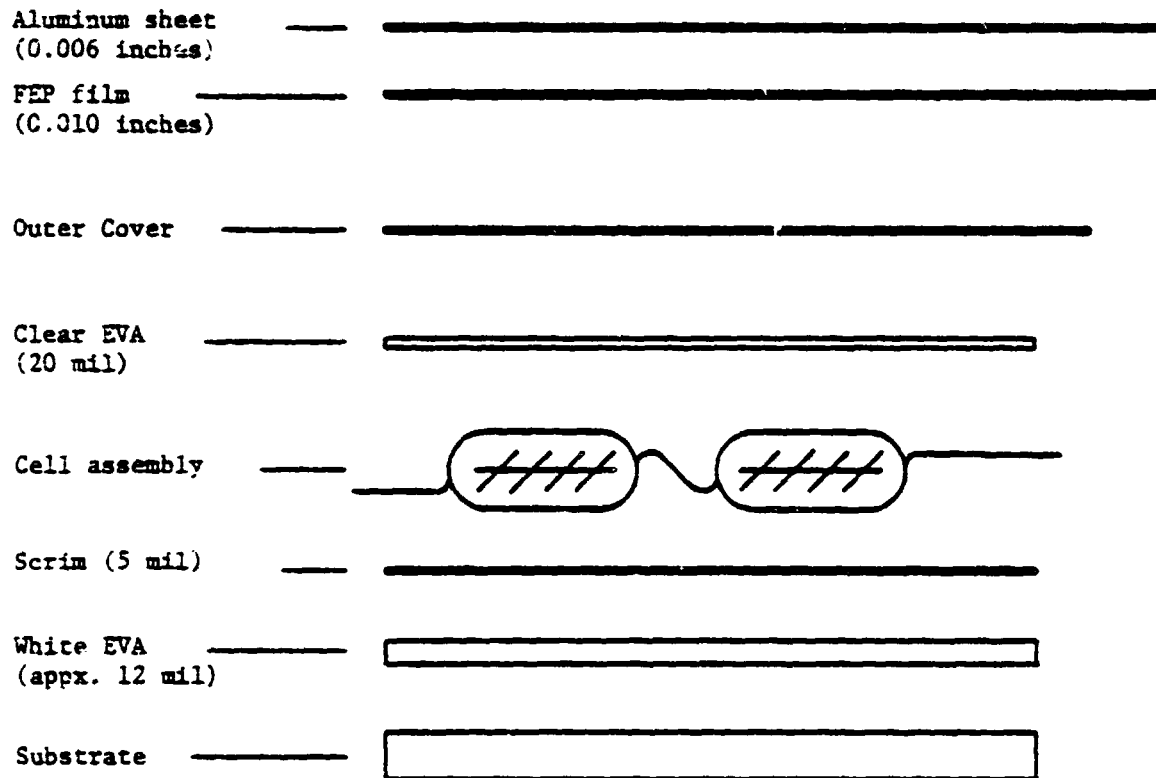
Module Fabrication Procedure

1. Load assembled module into vacuum bag and pump both cavities to 30 in.Hg for a period of 20 minutes.
2. Load into preheated platten press to heat module at approximate rate of 4°C/min. Both cavities are kept fully evacuated.
3. At a temperature of 120°C the pressure of the upper cavity is gradually released and permitted to come to room pressure over a 10 minute period.
4. The assembly is left in the press for 10 minutes after a temperature of 140°C has been reached, then removed with the lower cavity still under evacuation.
5. The module is removed from the vacuum bag after cooling for 10 minutes.

Figure 9

Module Layup - Substrate Design^a.

(Vacuum bag fabrication technique)

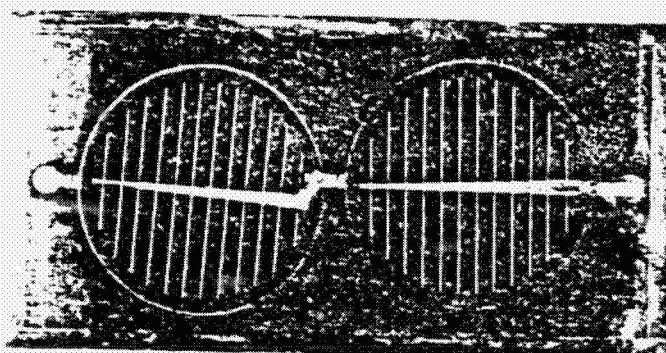


Note: Layup as shown above is secured by sealing the edges with masking tape.

- a. Superstrate design is similar, but uses the following order of materials:
from topside: glass, clear EVA, cells, scrim, white EVA, FEP film, aluminum sheet.

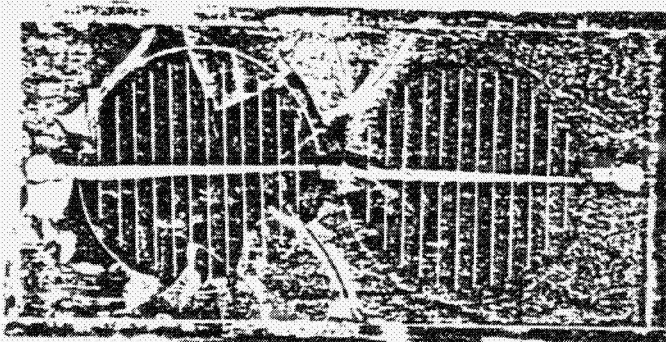
Figure 10

FAILURE OF SYLGARD 184/TEDLAR (100-BG-20TR) MODULE
(NEMA G-10 SUBSTRATE)



EMMAQUA EXPOSURE, 8 MONTHS

- . DARKENING OF SUBSTRATE WITH DEFIBERIZATION
- . DELAMINATION OF COVER PLUS EMBRITTLEMENT



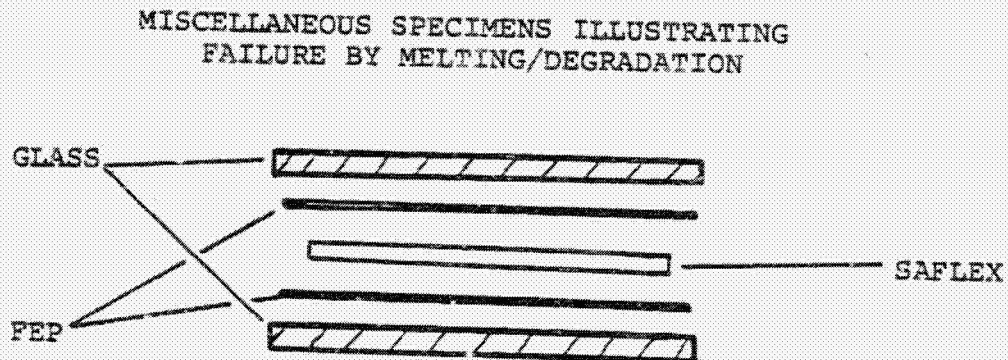
WEATHER-OMETER, 8-MONTH EXPOSURE

- . DELAMINATION AND CRACKING OF COVER
- . DARKENING AND DEFIBERIZATION OF SUBSTRATE

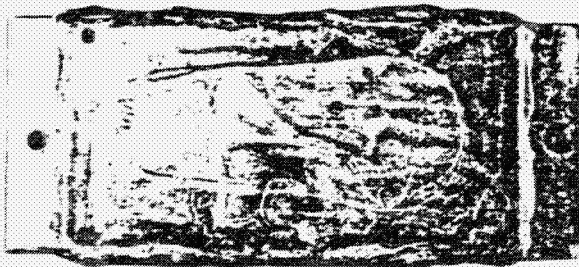
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FIGURE 11

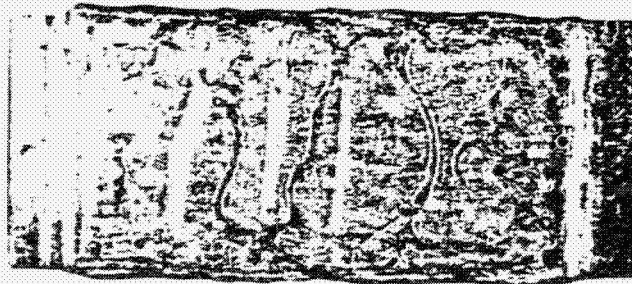
SAFLEX PT EXPOSURE
(PLASTICIZED POLYVINYL BUTYRAL)
GLASS-FEP FILM SANDWICH



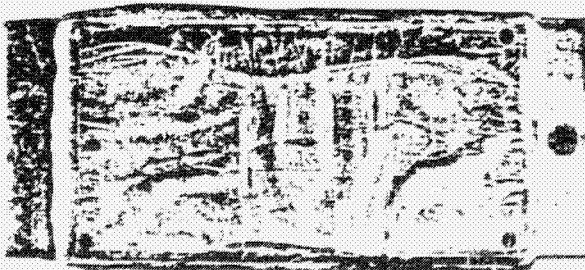
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OF POOR QUALITY



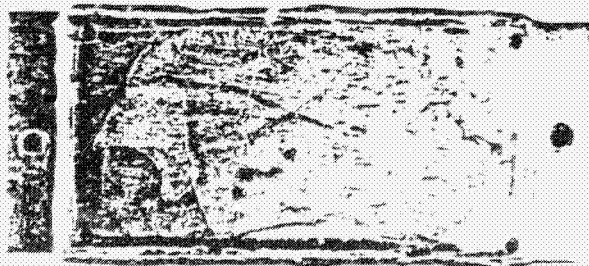
FLORIDA
FIXED ANGLE, 45°S
12 MONTHS



EMMAQUA
DESERT SUNSHINE TESTS
8 MONTHS



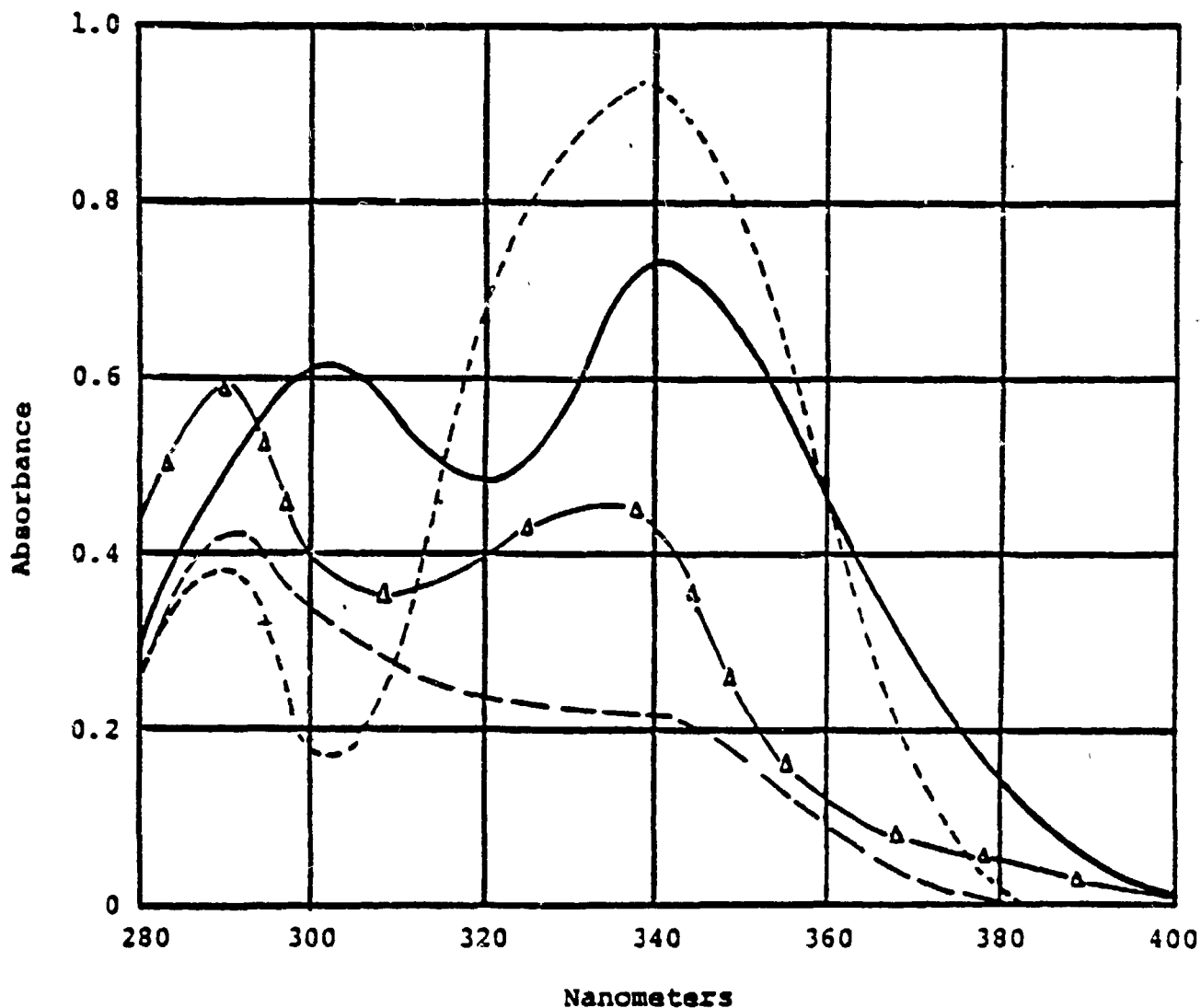
FLORIDA
FIXED ANGLE, 45°S
6 MONTHS



PHOENIX
FIXED ANGLE, 45°S
12 MONTHS

Figure 12

ULTRAVIOLET ABSORBERS
Comparison of Commercial Compounds
(10 mg/Liter, 1 cm Cell)



| | Compound | Absorptivity | Maxima, nm |
|-----------|-----------------|--------------|------------|
| ———— | Tinuvin-P | 70 | 340 |
| ----- | Naftone UV-340 | 129 | 338 |
| - - - - - | Permasorb-MA(1) | 43 | 290 |
| -Δ-Δ- | Cyasorb UV-531 | 48 | 290 |

* Acrylic copolymer from National Starch